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DEVELOPMENT OF A MONOLITHIC FERRITE MEMORY ARRAY

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16. Abstract

The results of the development and testing of ferrite monolithic memory arrays are presented. This development required the synthesis of ferrite materials having special magnetic and physical characteristics and the development of special processes; (1) for making flexible sheets (laminae) of the ferrite composition, (2) for embedding conductors in ferrite, and (3) bonding ferrite laminae together to form a monolithic structure. Major problems encountered in each of these areas and their solutions are discussed. Twenty-two full-size arrays were fabricated and fired during the development of these processes. The majority of these arrays were tested for their memory characteristics as well as for their physical characteristics and the results are presented. The arrays produced during this program meet the essential goals and demonstrate the feasibility of fabricating monolithic ferrite memory arrays by the processes developed.

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (continued)

TABLES

DEVELOPMENT OF A MONOLITHIC FERRITE MEMORY ARRAY

by

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1.0 INTRODUCTION

A comprehensive explanation is given in this report of the work performed and processes developed for the fabrication of monolithic ferrite memory arrays.

A monolithic ferrite memory array is a thin laminate of magnetic ferrite material into which are embedded two orthogonal sets of conductors, the word conductors and the digit-sense conductors, with the dimensions shown in Fig. 1. These two sets of conductors are separated from one another by ferrite material to provide the necessary electrical isolation. Information is stored in a monolithic ferrite memory array by controlling the magnetic state of the ferrite material immediately surrounding the intersection of each word and digit-sense conductor. To increase the sense signal level and to improve the signal-to-noise ratio, two crossovers are used for the storage of each information bit.

The work under Contract NAS1-8170 was divided into two sequential phases: materials synthesis and array development. The goals of the first phase were required to be met prior to initiating work toward the Phase II objectives. The Phase I objectives were to synthesize a ferrite composition and to develop a firing treatment to meet the following magnetic and physical characteristics:

Coercive force	$\leq$ 0.5 oersteds
Squareness ratio	$\geq$ 90 percent
Grain size	$\leq$ 10 microns
Remanent flux density	$\geq$ 1000 gauss
Resistivity	$\geq 10^6$ ohm-cm
Curie temp.	$\geq$ 300°C
Switching coefficient	$\leq$ 0.5 Oe-μsec

The Phase II objectives were to develop the processes required to fabricate monolithic memory arrays, using the material synthesized in Phase I. The arrays were to have the following physical and magnetic characteristics:

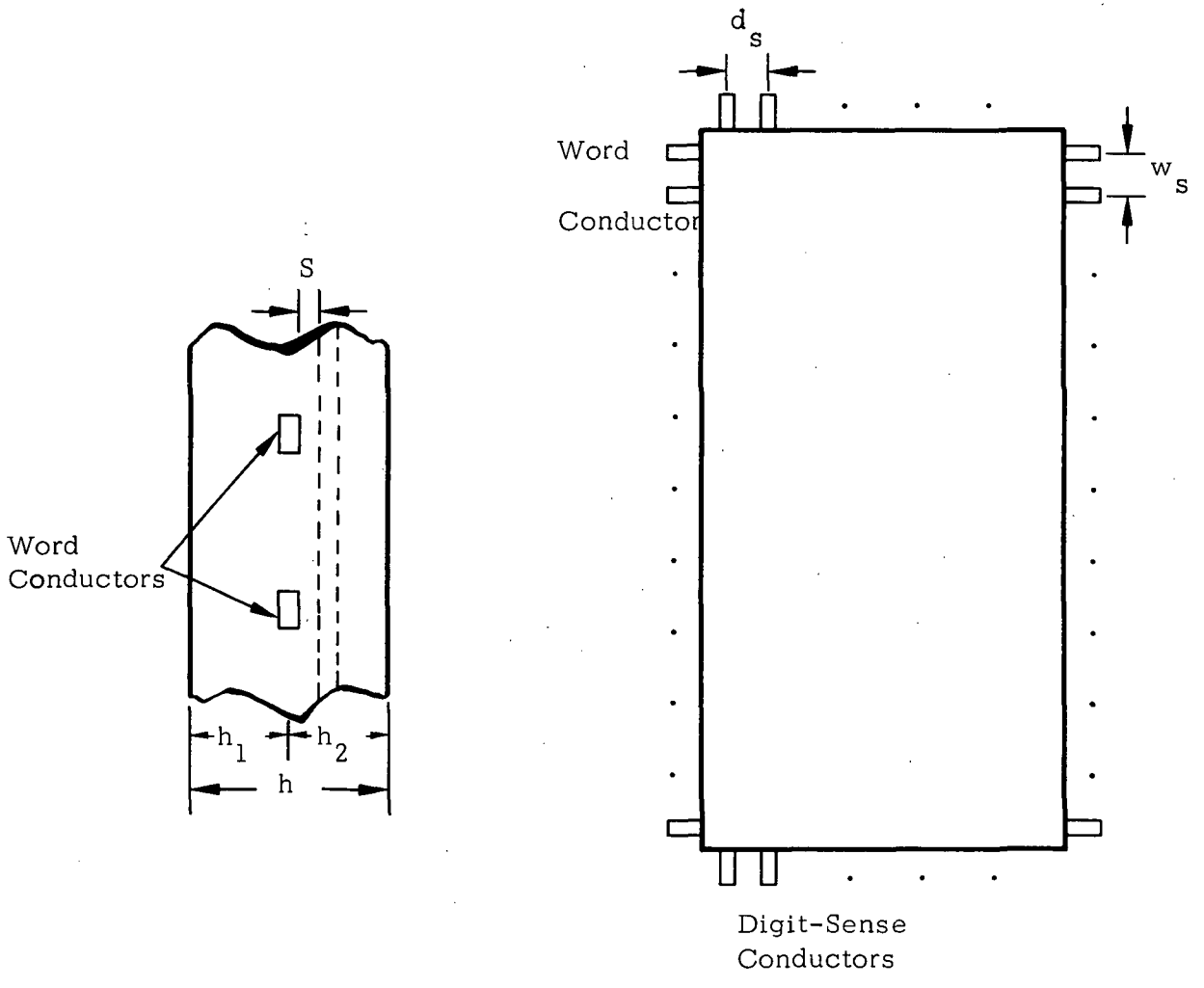

Fig. 1 Monolithic Memory Array Dimensional Characteristics

Number of word conductors	270
Word conductor spacing (w_s)	$\leq$ 12 milli-inch centers
Number of digit-sense conductors	70
Digit-sense conductor spacing (d_s)	$\leq$ 12 milli-inche center
Ferrite array height (h)	$\leq$ 10 milli-inches
Word conductor resistance (R_w)	$\leq$ 3 ohms/inch
Digit-sense conductor resistance (R_s)	$\leq$ 1 ohm/inch
Disturbed signal flux	$\geq$ 0.1 maxwell
Ratio of height above word conductor center to the height below (h_1/h_2)	$\geq$ 1
Height below word conductor center (h_2)	$\leq$ 0.42 w_s
Spacing between word conductor and digit-sense conductor(s)	$\leq$ 0.5 milli-inches
Coupling resistance between a word and a digit-sense conductor (R_c)	$\geq 10^8$ ohms
Distributed inductance per crossover of digit-sense line (L)	$\leq$ 6 nanohenries
Distributed capacitance per crossover of digit-sense line (C)	$\leq$ 0.1 picofarad
Digit-sense line attenuation per crossover (α)	$\leq 1.5 \cdot 10^{-3}$ db
Digit-sense line delay per crossover (τd)	$\leq$ 25 picoseconds
Disturb signal ratio (uV/dV)	$\leq$ 1.3
Disturb sensitivity ratio (D_s/dV)	$\leq$ 0.3

2.0 FERRITE POWDER PROCESSING

The processes which were used for the synthesis of materials in this program are shown in Fig. 2. All of the steps shown, however, were not used for the synthesis of each composition. The compositions which were prepared in Phase I fall into two general categories: substituted lithium ferrite and substituted zinc magnesium manganese ferrite.

Twenty-six[1] compositions were prepared and evaluated. Four of these compositions were found to have characteristics which either closely approached or exceeded the target objectives. Composition LM-71B was recommended to be used for fabrication of arrays in Phase II and the other three were recommended for further evaluation and as alternate materials for array fabrication. The formula for each of these compositions is given in Table 1.

Table 1 Recommended Compositions

Composition Number	Composition
LM-71-B	$Mg_{.864}Mn_{.432}Zn_{.114}Fe_{1.728}O_4$
LM-84-1	$Mg_{.826}Mn_{.413}Zn_{.109}Fe_{1.652}O_4$ + 0.25% Ca
LM-85-1	$Mg_{.575}Mn_{.525}Zn_{.100}Fe_{1.800}O_4$ + 0.25% Ca
LM-86-1	$Mg_{.675}Mn_{.525}Fe_{1.800}O_4$ + 0.25% Ca

[1] Laminated Ferrite Memory, Phase I, Summary Report, June 1969. N. C. Bhiwandker and C.H. Heckler, Jr.

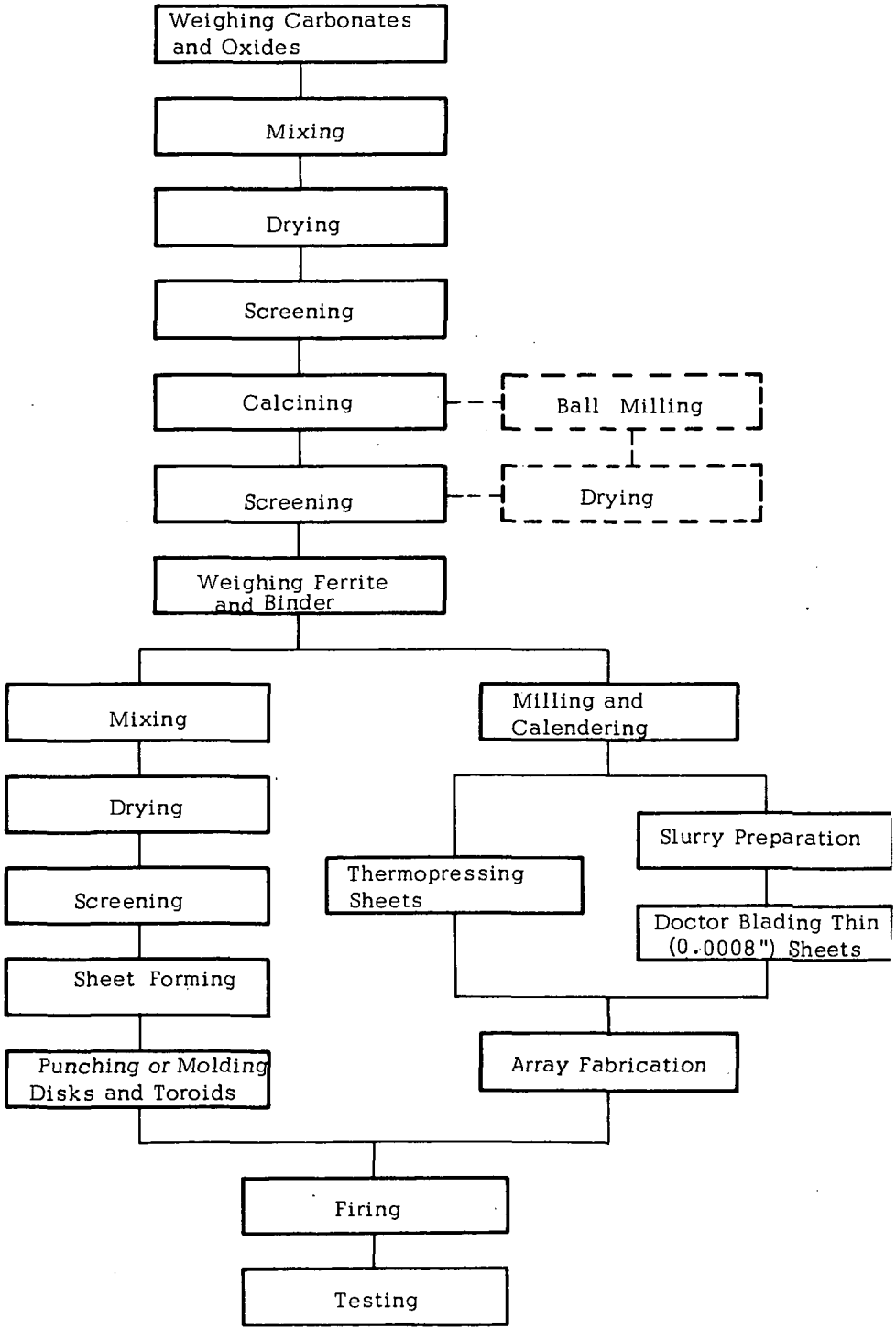

Fig. 2 Flow Diagram - Ferrite Processing

2.1 Starting Materials

In the synthesis of the compositions prepared for this program, all of the starting materials used, with the exception of the ferric oxide, were reagent grade materials. These materials are powders consisting of micron-size particles of the oxides, carbonates, and acetates of the constituent metal atoms. The fine particle size facilitates the thorough mixing required to obtain a homogeneous chemical composition. To determine the amount of each starting material required for the synthesis of a specific composition, it is necessary to know the assay of each starting material. The assay and trace impurity analysis and the particle size of the lots of starting materials used are given in Tables 2 to 6. The trace elements, while not treated as a part of the composition formula, can in certain instances significantly affect both physical and magnetic characteristics of the final composition. It is therefore necessary that a quantitative determination of the trace elements of the starting materials be made. With the exception of substances not precipitated by $(NH_4)_2S$ as (SO_4) and water soluble salts, the level of each impurity is well below a tenth of a percent in the starting materials used. Batches of three sizes have been prepared in this program. They weigh, after calcining, 150 grams, 1500 grams, and 6000 grams. The accuracy in the weighing of the starting materials was 0.05 grams. The particle size determination of the starting materials was made with a scanning electron microscope at a magnification of 10,000 diameters. Fig. 3 shows a scanning electron micrograph of the particles for the magnesium carbonate.

2.2 Mixing

To obtain a thorough mixing of the starting materials, the ingredients were ball-milled for 16 hours in a rubber-lined jar, using steel balls and alcohol as the vehicle. The ratio of the alcohol (H_2O for compositions with Ca) to the dry powders was kept at 6:1 for the different batch sizes. The slurry from the steel jars, after being emptied into stainless steel drying pans, was oven dried. The mixed starting materials for composition LM-71-15 are shown in the scanning electron micrograph of Fig. 4.

2.3 Calcining

The dried powders of mixed starting materials were poured into alumina saggers and loaded into the calcining furnace. All of the recommended compositions with the exception of the LM-71B were calcined at 900°. The LM-71B composition was calcined at 1000°C. During calcining, the carbonates and acetates are converted to oxides, formation of the spinel structure is initiated, and particle size is increased through the sintering

Table 2 Assay and Trace Impurity Analysis: Fe_2O_3

Fe_2O_3

C. K. Williams. Cat. No. R2199R, Lot 8
Assay and Analysis of Trace Impurities

	Percent
Fe	99.3
Si	0.015
Mn	0.08
Mg	0.015
Al	0.006
Mo	< 0.005
Cu	< 0.001
Ni	0.007
Ca	0.025
Cr	0.002
Particle Size	1.5 μ

Table 3 Assay and Trace Impurity Analysis: ZnO

ZnO

Baker Analyzed Reagent
J. T. Baker Chemical Co.
Cat. No. 4358. Lot No. 32148

	Percent
Assay	100.0
Insol. in H_2SO_4	0.005
Alkalinity	Pass ACS Test
Chloride (Cl)	0.0003
Nitrate (NO_3)	0.001
Sulfur Compounds (as SO_4)	0.002
Arsenic (As)	0.00004
Iron (Fe)	0.0002
Lead (Pb)	0.0003
Manganese (Mn)	0.0002
Substances not precipitated by $(NH_4)_2S$(as SO_4)	0.09
Particle Size	1 - 10 μ

Table 4 Assay and Trace Impurity Analysis: $MgCO_3$

$MgCO_3$

Baker Analyzed Reagent
J. T. Baker Chemical Co.
Cat. No. 2432 Lot No. 33328

	Percent
Assay (as MgO)	41.7
Insol. in HCl	0.008
Chloride (Cl)	0.001
Sulfate (SO_4)	0.005
Calcium (Ca)	0.018
Heavy Metals (as Pb)	0.001
Iron (Fe)	0.002
Water Soluble Salts	0.35
Particle Size	9 - 25μ

Table 5 Assay and Trace Impurity Analysis: $MnCO_3$

$MnCO_3$

Baker Analyzed Reagent
J. T. Baker Chemical Co.
Cat. No. 2536

	Lot 22632 Percent	Lot 33171 Percent	Lot 38116 Percent
Assay (as Mn)	44.6	44.9	43.0
Insol. in HCl	0.002	0.002	0.01
Chloride (Cl)	0.010	0.020	0.02
Sulfate (SO_4)	0.002	0.002	0.005
Substances not precipitated by $(NH_4)_2S$(as SO_4)	0.08	0.08	0.20
Other Heavy Metals (as Pb)	0.002	0.004	0.005
Iron (Fe)	0.001	0.002	0.002
Zinc (Zn)	0.05	0.010	0.05
Particle Size	-	-	1 - 20 μ

Table 6 Assay and Trace Impurity Analysis: $Ca(CH_3COO)_2$

Ca Acetate

J. T. Baker
Lot 26676

Assay $(CH_3COO)_2 Ca \cdot H_2O$	100.2%
Insoluble in HCl and NH_4OH precipitate	0.001%
pH of 5% solution at 25°C	7.7
Chloride (Cl)	0.0005%
Sulfate (SO_4)	0.007%
Nitrogen Compounds (as N)	0.002%
Barium (Ba)	0.001%
Heavy Metals (as Pb)	0.0005%
Iron (Fe)	0.0001%
Magnesium and Alkalies (as SO_4)	0.10%
Particle size range	30 - 300 μ

10,000 X

Fig. 3 Scanning Electron Micrograph of $MgCO_3$, Lot 33328

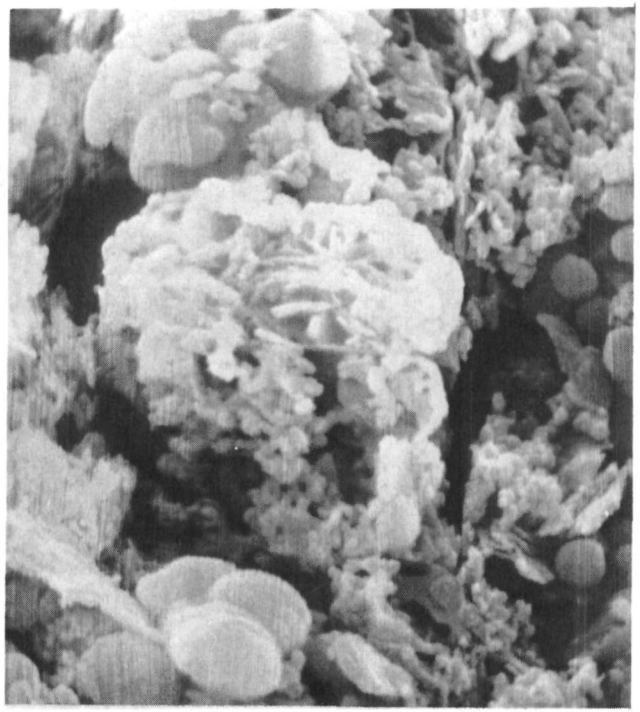

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Fig. 4 Scanning Electron Micrograph of Mixed Starting Materials for LM-71-15 Compositions

process. Fig. 5 shows a scanning electron micrograph of the particles of the LM-71-14 composition after calcining.

2.4 Milling

The post-calcination milling step consisted of ball milling a calcined powder for 16 hours in steel jars charged with steel balls. Alcohol was used as the vehicle in a ratio of 6:1 with respect to the powder. Experiments were conducted to determine the effects on the magnetic characteristics of omitting the milling step. These tests indicated little or no change in the magnetic characteristics due to the omission of the post-calcination milling step.

Scanning electron micrographs have shown little change in the particle size after milling. This may be seen by comparing the scanning electron micrographs of milled LM-71-12 material in Fig. 6 with the unmilled LM-71-14 material in Fig. 5. Since the detectable differences were slight, the post-calcination milling step was eliminated in the processing of the LM-71 material during Phase II.

2.5 Binders

The fabrication process used for making monolithic ferrite memory arrays was based on the use of flexible ferrite sheets. For this reason, binder systems which give flexible sheets were used exclusively throughout this program. This procedure had the advantage of giving characteristics during the material evaluation phase which could be expected to be obtained in fabricated arrays. Two binder systems were used: a Butvar system, and a Polyvinyl Chloride system. The Butvar system was used only in Phase I for the evaluation of the materials. Previous experience with this binder system had shown that it did not react chemically with a wide range of ferrite compositions to alter their magnetic characteristics. The Butvar binder system was added to the ferrite powder by mixing in a ball-mill for 16 hours, using toluene as a solvent. The percentage of the Butvar binder was 16%, by weight, of the ferrite powder.

In Phase II it was desired to use a calender mill for the preparation of the flexible ferrite sheets. The binder system was changed to the PVC system, whose characteristics are well suited for calender-milling. The polyvinyl chloride binder was mixed directly with ferrite powder by milling on the calender mill. A slurry was first formed by dissolving the polyvinyl chloride in methyl ethyl ketone and adding the ferrite powder to the solution. The percentage of the polyvinyl chloride binder system used was 16-1/2%, by weight, of the ferrite powder.

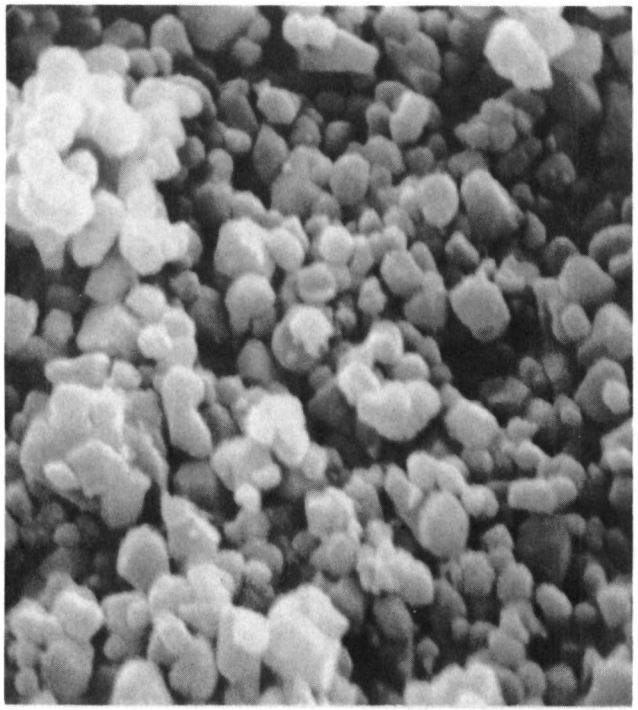

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Fig. 5 Scanning Electron Micrograph of Calcined LM-71-14 Composition

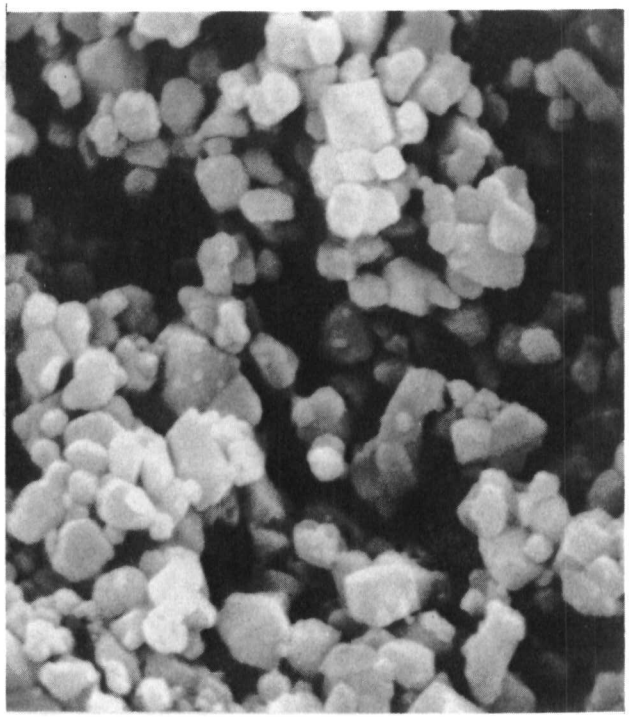

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Fig. 6 Scanning Electron Micrograph of Ball Milled LM-71-12 Composition

2.6 Firing

The firings of the toroid samples were made in laboratory tube furnaces with controlled atmosphere capability. The firings that gave the best combination of magnetic and physical characteristics consisted of heating in an oxygen atmosphere and cooling in a nitrogen atmosphere. A firing temperature of 1350°C was used to obtain the characteristics listed in Table 7 for three of the recommended compositions, LM-71B, LM-84-1, and LM-85-1. The LM-86-1 was fired at 1325°C to obtain the listed characteristics. The heating rates used were 100°C, and 150°C per hour after a binder burnoff firing with a 27°C per hour rise to 455°C. Cooling of toroidal samples was at the natural cooling rate of the furnace, which had an initial slope of 500°C per hour and cooled to 100°C in 27 hours.

Table 7 Static Characteristics of Recommended Compositions

	Calcining			Firing						
	Temp (°C)	Time (hours)	Time (°C)	Time (hours)	Atmos Heat-Soak-Cool	H_c (Oe)	B_r (Gauss)	B_r/B_m	μ (Microns)	ρ (Ohm-cm x 10^6)
LM 71-B-4	1000	16	1350	24	O_2/N_2	0.67	1573	95	17	66.9
LM 84-1	900	4	1350	24	O_2/N_2	0.41	1438	96	14	16.6
LM 85-1	900	4	1350	24	O_2/N_2	0.37	1634	97	20	1.3
LM 86-1	900	4	1325	4	O_2/N_2	0.62	1263	95	18	8.6

3.0 FABRICATION OF FERRITE SHEETS

In order to realistically evaluate the materials during Phase I of this program, toroids were punched from flexible ferrite sheets rather than by conventional dry powder pressing--where a smaller binder content is used--which results in different density and magnetic characteristics. The flexible sheets were prepared by a thermopressing process using the Butvar binder system. For the development of the array fabrication process in Phase II, flexible ferrite sheets for the word and digit-sense laminae were prepared by the calender-mill process. The thin center sheets were prepared by doctor-blading.

3.1 Thermopressing Process

Preparation of flexible ferrite sheets by the thermopressing process required that the ball-mixed slurry be formed into a powder after drying. Drying was accomplished by pouring the slurry of binder and ferrite powder from the steel jars used for ball mixing into large stainless steel drying trays which were dried at room temperature under forced circulation to prevent preferential settling of the ferrite particles. The material was removed from the drying trays and forced through a 20-mesh screen to form a coarse powder. Sheets 2.25 inch x 0.8 inch were formed by placing a measured quantity of the powder in a die cavity, inserting a plunger, raising the temperature of the die to 85 °C and applying a force of 8000 lbs. to produce thermoplastic flow. The thickness of the sheets produced was determined by the amount of the powder inserted at the beginning of the process. Typically the sheets prepared for Phase I evaluation were 48 mils thick. Sheets formed by this process were of good quality and were free from air holes. The thermoplastic flow characteristic of the binder system causes the flexible sheet to be formed as a dispersion of ferrite powder embedded in a solid binder matrix rather than as an aggregate of compacted particles.

3.2 Calender-Mill Process

For preparing flexible sheets on the calender mill, the PVC binder system was used, since this binder does not undergo changes in its characteristics at the temperature and working time required for this process.

The calender mill used was an EEMCo 3 x 3 x 8 laboratory mill, with 3" rollers and with roller speed ratios of 1:1 and 1.4:1. The temperature of the rollers was controlled at 80°C. Forty minutes of milling were used to intimately mix binder and powder. At the end of the binder mixing step, the material was removed from the mill as a coarse-surfaced sheet. The 7 mil and 4-1/2 mil sheets required for the word and digit-sense laminae of the monolithic memory array were prepared by cutting 1" x 4" pieces from the calendered sheet and then thermopressing the pieces to the desired thickness. The thermopressing was performed on a Carver hydraulic press at a controlled platen temperature of 150°C. The thickness of the sheets was controlled by using shims to limit the closing of the platens. One mil Teflon backing sheets were used to prevent the sheets from sticking to the platens. After pressing the flexible sheets to size, the backing sheets were easily removed, as the Teflon provides a good release surface for the PVC binder. This method of sheet preparation consistently yielded sheet thicknesses uniform within 0.0002 inches.

3.3 Doctor-Blade Process

Preparation of the thin 0.0008 inch sheets has been successful consistently only by the doctor-blade process. Attempts at preparing thin sheets less than 0.001 inch by the thermopressing process resulted in sheets having a number of pinholes. For doctor-blading, use of a glass substrate has resulted in the highest yield of thin sheets. Even though Teflon has better release characteristics for the PVC system, the release from Teflon is not good enough to permit stripping of the sheet from the substrate without stretching or tearing the sheet. A hard glass substrate permits removal, however, of the sheets by scraping with a sharp blade.

To prepare doctor-bladed sheets a slurry was first formed by shaking the powder, solvent, and PVC binder in a plastic container on a paint shaker for 1 hour. A small number of steel balls were added in the plastic container to promote thorough mixing of the slurry. To form a sheet, a small quantity of the slurry was poured on the glass substrate and spread to a uniform thickness with a doctor-blade. As a consequence of the thinness of the sheets, the drying time is very short. The sheets completely dry within an hour. The removal process is simplified by the tendency of the thin sheet to curl and form a tubing as the blade separates it from the glass substrate. After the full length of the doctor-bladed sheet was freed from the substrate, the material easily unrolled to form a flat sheet.

4.0 FABRICATION OF TOROIDS AND DISCS

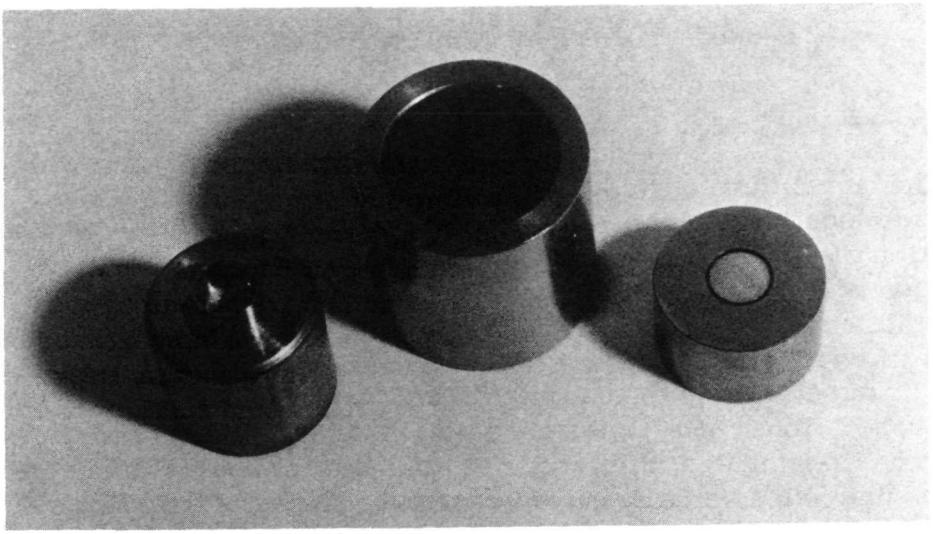
In the monolithic ferrite array the geometry of the flux pattern at the bit storage locations is not well defined and therefore is not suitable for the evaluation of magnetic characteristics of materials. It follows that memory operation of a monolithic array cannot be completely predicted when such predictions are based upon magnetic characteristics determined by use of the well-defined geometry of a toroid. However, to evaluate the basic magnetic characteristics of the materials prepared in Phase I, toroidal samples were used. Toroidal samples have also been used as controls in firings of arrays. To minimize differences in characteristics due to differences in processing, all toroidal samples have been prepared from flexible ferrite sheets which were formed either by thermopressing from powder or by calender milling, as described in the preceding section.

4.1 Punched Toroids and Discs

All of the toroids used in the Phase I material evaluation were prepared by punching from thermopressed sheets. Two sizes of toroids were punched from these 0.045 inch thick sheets. The small toroids were 0.080 inch ID and 0.115 inch O.D. The larger toroids were 0.352 inch ID and 0.390 inch OD. Discs 0.210 inch in diameter and 0.045 inch high were also punched for resistivity and grain size measurements. Punching of both toroids and discs was accomplished with the conventional hardened steel punch and die sets shown in Fig. 7.

4.2 Molded Toroids

During Phase II, the process for preparing small toroids was changed from punching to molding to improve the uniformity of the cross sectional area. During punching the sheared surfaces forming the inside and outside diameter on the punched toroids were variably irregular. After the process was changed to molding, these formed surfaces were as smooth and as regular as the top and bottom surfaces. Accurate determination of many of the magnetic characteristics requires that the toroid samples have a highly uniform cross sectional area along the magnetic path. Use of the molded toroids therefore improved the accuracy of these measurements. The mold used to form toroids is shown in Fig. 8. In this mold, up to twenty-seven toroids can be molded at one time. Toroids formed were 0.050 inch ID, 0.085 inch OD and 0.045 inch high.



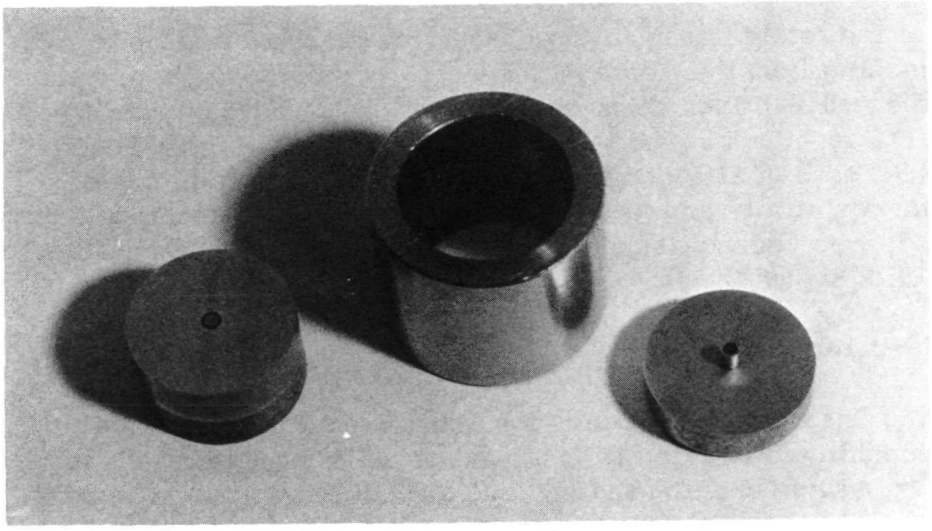


Fig. 7 Toroid and Disc Punch Sets

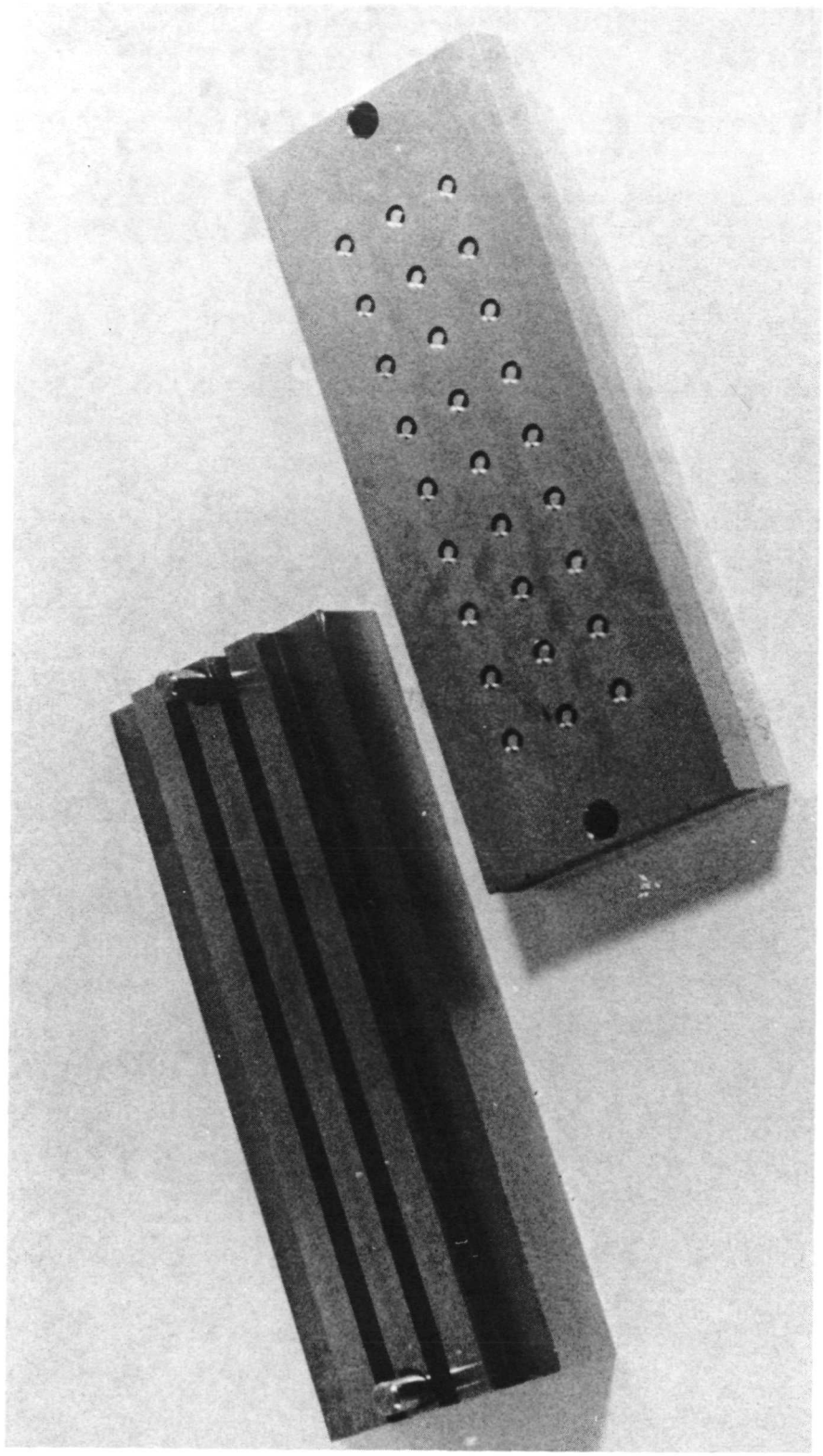


Fig. 8 Toroid Mold

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5.0 CONDUCTOR PROCESSES

One of the most critical processes required for the development of monolithic ferrite memory arrays is the process for embedding conductors within the ferrite. Strains in the ferrite due to differential shrinkage during firing, between the embedded conductors and the surrounding ferrite, must be minimized to prevent rupture of the ferrite. The shrinkage obtained in the ferrite sheets prepared during this program has been between 18 and 20 percent. To minimize the strains in a material with this amount of shrinkage, two approaches were investigated: (1) Space between the conductors and the ferrite was provided to allow for the shrinkage of the ferrite, and (2) Conductor material was used that shrank during firing. There were further restrictions on which materials could be used. The melting temperature of the conductors had to be greater than 1350°C and the conductivity of the material was desired to be as high as possible. Platinum, palladium, and a platinum-palladium-gold alloy were the metals used in the conductor experiments. The platinum-palladium-gold alloy was used for the conductors in all of the full-size arrays made.

5.1 Powder Conductors

The process of forming conductors from a powder of fine metal particles involved the following steps: 1) embossing a channel in a ferrite sheet, 2) filling the channel with a fine metal powder, 3) bonding to other ferrite sheets to form a laminate, and 4) firing the laminate at 1350°C. This process was first tried using platinum black and palladium black powders. The volume shrinkage of these powders, however, was excessive. Conductors formed by filling 0.002" deep channels and firing at 1350°C were too thin to be detected by x-radiograph.

The large shrinkage of the platinum-black and the palladium-black powders is explainable by the particles having an irregular shape with a large surface-to-volume ratio. Addition of binder to the platinum-black powder to form a paste did not measurably change the amount of shrinkage. Doctor-bladed samples of platinum-black paste had a volume shrinkage of 97% after firing at 1350°C.

Densification of the platinum- and palladium-black powders was attempted by calcining the powders at temperatures between 550°C and 750°C. Insufficient densification occurred at the lower temperatures to limit the linear shrinkage during final firing to the required 20 percent. At the higher temperatures, where sufficient densification did occur, the particles sintered together to form large particles. Subsequent grinding of the calcined powder to form smaller particles did not produce sufficiently uniform-sized particles to be useable. Conductor lines prepared from pastes of these calcined particles generally opened during the final firing.

5.2 Paste Conductors

The shrinkage of paste conductor materials was determined by doctor blading small quantities of paste to form sheets which were then measured after drying and firing. Table 8 lists the linear shrinkage obtained for the pastes used.

Due to the large shrinkage encountered with the Pt black powder and the problem of particle-size control associated with the calcined Pt black powder, further investigation of processes using Pt black was considered unlikely to yield a useful conductor process and was terminated.

The filling of embossed channels with pastes made from calcined Pt and Pd black introduced the problem that the solvents in the paste dissolved the binder in the ferrite sheets. To prevent this, two different binder systems were required. The one for the paste had to be soluble in a solvent that did not dissolve the binder in the ferrite sheets. Pine oil, a solvent that is used in vehicles for paints and inks, did not dissolve the PVC binder. Two proprietary binders which contain pine oil as the solvent were found. One was a squeegee medium, Type 163C, manufactured by L. Reusche and Co. The other was the binder used in certain of E.I. DuPont's precious metal electrode compositions: DP8283, 8272, and 8013.

The formation of conductors by filling embossed channels with the DuPont pastes gave variable results. The palladium paste caused the laminates to crack and the platinum alloy pastes gave conductors so thin as to be barely detectable by x-radiograph. The conductor resistance measured on the uncracked laminates was high and ranged between 10 and 40 ohms per inch. The variable resistance was due to the drying, and a resultant shrinkage, of the paste during the filling operation. The Pt alloy paste had a wet-to-dry shrinkage of between 71 and 78 percent and a specified drying time of from 10 to 80 minutes, dependent upon composition type, lot number, and thickness. The needs to fill the channels to a controlled level relative to the surface of the embossed sheet and to keep the paste off the surfaces between channels were additional drawbacks to the process.

Four methods used in filling channels with conductor paste were: (1) unaided filling of the channels, (2) use of a stencil, (3) overfilling channels and scraping away excess paste while wet, and (4) overfilling channels and scraping away excess paste after drying. Of the four, the use of a stencil was the most effective. Stencils of varying thickness were used to compensate for the wet-to-dry shrinkage and to protect the surface of the ferrite lamina between channels during the filling operation. The Pt alloy and Pd pastes were not thixotropic and therefore the stencil had to be held in place until the paste thickened, to prevent it from spreading. When dry, portions of the paste stuck to the stencil, giving rise to broken conductor lines or variable line thickness and resistance.

Two other methods of filling embossed channels were used. These additional methods involved formation of conductor sheets from the paste, from which conductor lines were cut and laid in the embossed channels. In the first method, the conductors were cut from the dry sheets formed by doctor-blading the paste on a teflon substrate. In the second method the conductor lines were punched from doctor-bladed sheets which had been bisque fired to densify the sheets so that the remaining shrinkage of conductors punched from these sheets would match the shrinkage of the ferrite sheets.

Figure 9 shows the results of experimental firings which were run to determine the bisque firing temperature of the DuPont 8283 Pt alloy paste. Conductors punched from bisque fired sheets were required to have 21 percent linear shrinkage when fired at 1350°C. After bisque firing, the conductor sheets were sufficiently flexible to be easily handled and sufficiently brittle to be accurately punched. Conductors 0.003 inches, 0.005 inches, and 0.006 inches wide and 4.25 inches long have been made by punching from .0022 inch bisque fired sheets. The uniformity of the punched conductors has been very good, with approximately 90 percent having a resistance within ±2 percent of the mean.

The dynamic and static shrinkage characteristics of both the Pt alloy conductor material and the ferrite sheets are shown in Fig. 10. The Pt alloy sheet used in this experiment was bisque fired at 850°C with a shrinkage of approximately 22%. This data shows that the shrinkage of the Pt alloy during sintering is a function of temperature while the shrinkage of the ferrite is a function of both temperature and time.

5.3 Solid Platinum Conductors

To embed solid conductors, which do not shrink during firing, in ferrite sheets, which do, requires that space be provided surrounding the conductors to allow for the ferrite shrinkage. This space prevents strains

Table 8 Linear Shrinkage of Paste Conductors

Paste	Supplies	Wet-to-Dry Shrinkage - %	Dry-to-Fired Shrinkage (1350°) - %
8013 (Pd)	E.I. DuPont	2	16.5
8273 (Pt alloy)	E.I. DuPont	78.7	36.5
8283 (Pt alloy)	E.I. DuPont	71.5	36.4
Pt alloy + 25% binder	E.I. DuPont	78.7	33.6
Pt alloy + 14.4% binder	E.I. DuPont	-	33.7
Pt alloy + 8% binder	E.I. DuPont	-	38.0
Pt black + 18% binder	WESCO	-	69.0

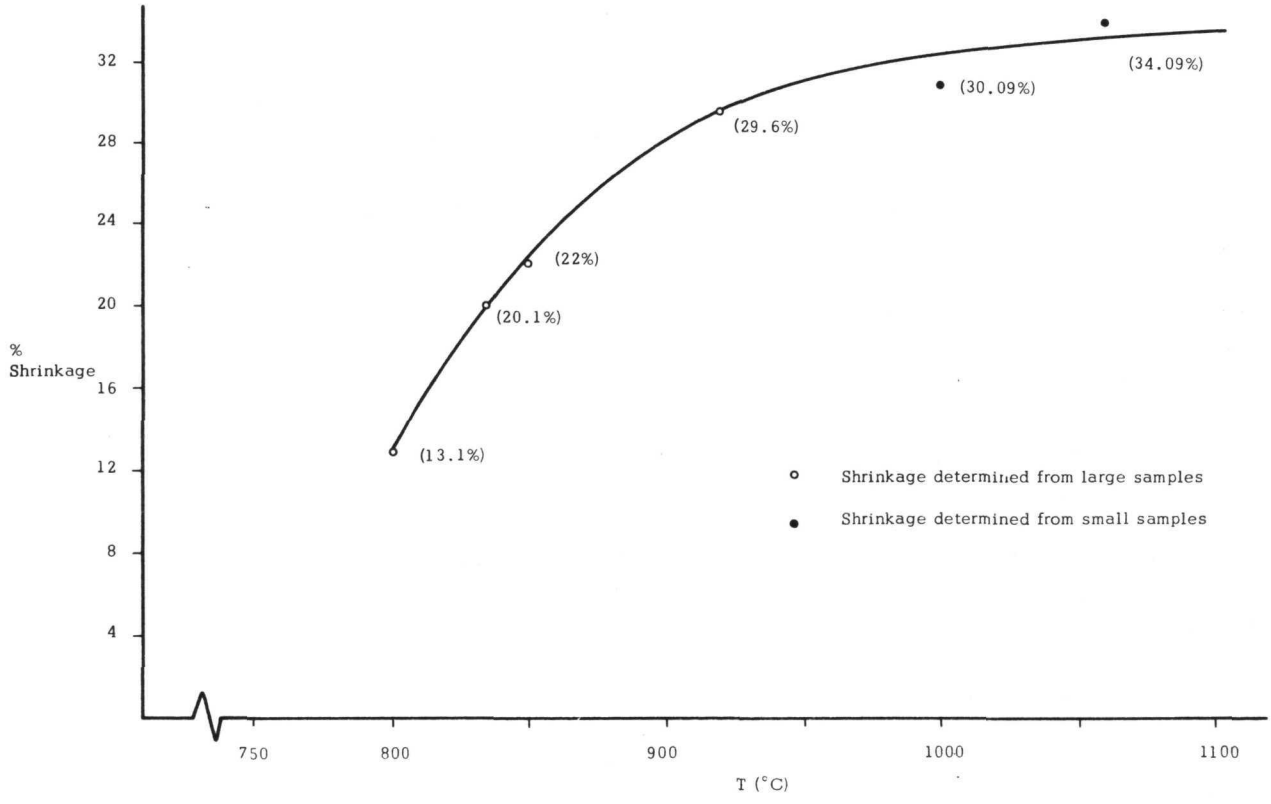

Fig. 9 Shrinkage of DuPont 8283 Pt-Alloy Conductor Sheets

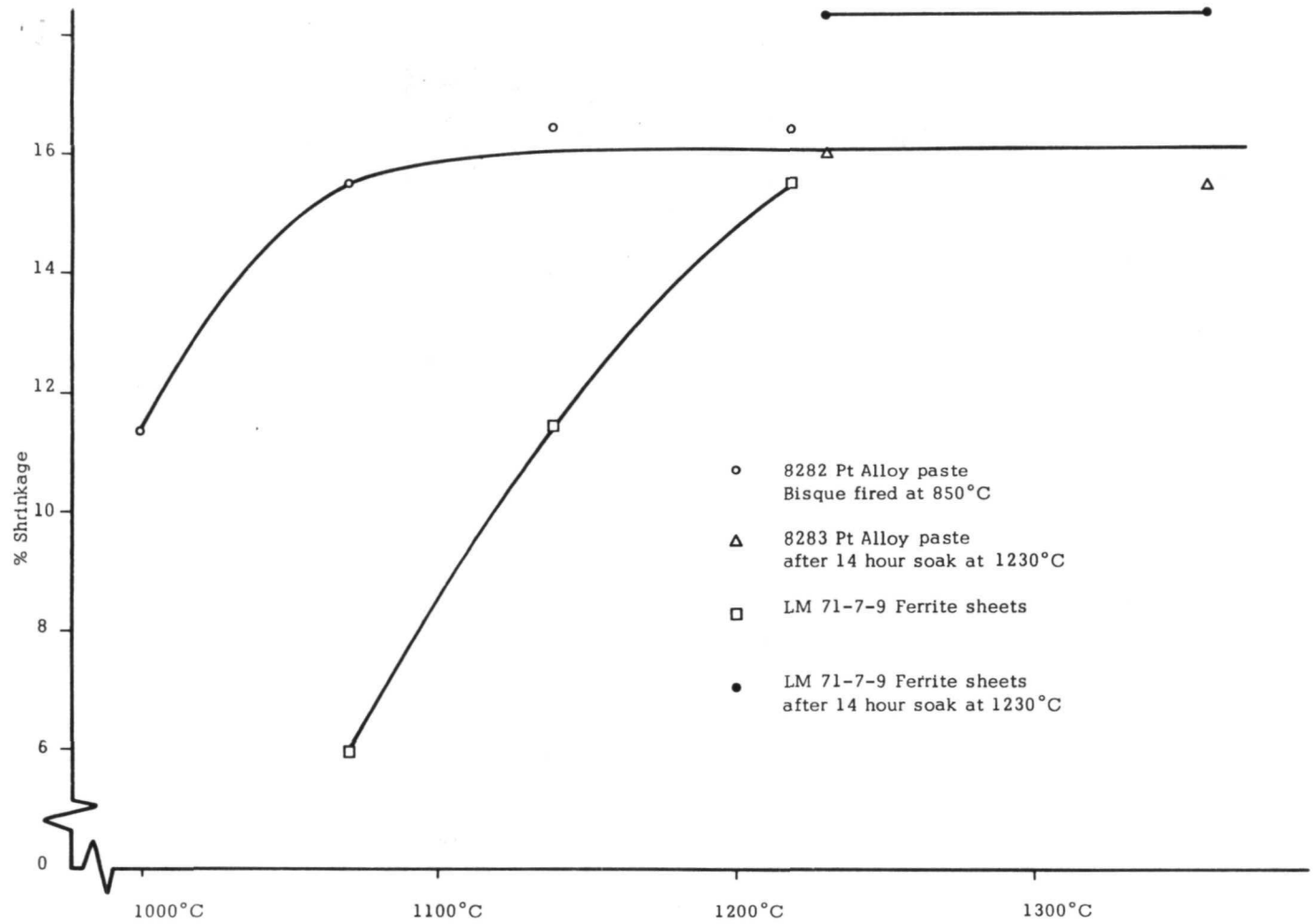

Fig. 10 Shrinkage of Pt-Alloy and Ferrite Sheets as a Function of Temperature and Time

from occurring which result in cracking of the ferrite. Two methods of providing this space were investigated: the first was to coat the conductors with a removable coating; the second was to emboss oversize channels.

The processes which were used to coat solid platinum conductors were drawcoating and electroplating. Several organic polymers were used in the drawcoating experiments. Beading of the organic coatings was a major problem. This could be controlled only by applying thin coatings. Attempts at applying multiple thin coats were unsuccessful as the undercoat was dissolved when the wire was reimmersed in the coating solution for additional coatings. For these coating experiments the organic thermoplastics, Butvar, methyl methacrylate, and a polyimide, Pyre ML, were used. With the Pyre ML, a polymerization step was used between coatings to prevent redissolving the underlayers. This process required an excessive number of coats to obtain the required thickness. In the electroplating process a coating of gold was plated over the platinum wire. During the firing the melted gold was expected to be forced out the ends of the ferrite sheet, thereby providing room for the ferrite to shrink. This did not happen and the laminates had distortions characteristic of an uncoated solid embedded conductor; short sections of longitudinally cracked ferrite, with loops of platinum visible or protruding, alternated with short sections of uncracked ferrite.

The process of embedding solid conductors in oversize embossed channels was used repeatedly with uniformly poor results; however, in these experiments all of the embossed channels were rectangular in cross section and the solid Pt conductors used were round. In a final experiment, the embossed channels were made by pressing into the lamina a No. 40 wire which was 80 percent larger in diameter than the 0.002 inch diameter Pt wire embedded in the channel. These laminates had a good physical appearance after firing, and x-radiographs showed the conductors to be straight and continuous. This result occurred after development of the bisque firing process for paste conductors and was not further developed due to lack of time.

6.0 ARRAY FABRICATION

The processes for fabricating 270 x 70 conductor monolithic memory arrays were developed initially using 1 inch square arrays with a single crossover. The number of conductors was then increased to form a 3 x 3 conductor array. From this, the array size was increased to full size - 4.2 inches x 1.2 inches - and the number of conductors was increased to progressively obtain 4 x 4, 4 x 8, and 8 x 12 crossovers. Finally eight fully-populated, full-size arrays were prepared.

6.1 Embossing

Embossing of the lamina was accomplished by thermopressing the lamina with an embossing mold at a force of 5000 pounds and at a temperature of 60°C. The problems encountered in this process step were to obtain good release of the lamina from the mold and to develop a process for making a mold. These problems were not unrelated. The release of laminae from the mold is a function, among others, of the smoothness of the mold surfaces. The initial molds were made by photoetching steel. The mold surface is the reverse of the pattern to be embossed, so the channels were the raised or unetched portion of the mold. The remaining surface of the mold was etched to the depth of the channels. For 0.003 in. wide channels, 80 percent of the mold surface was etched. This etched surface was microscopically irregular and therefore made release of the molded lamina very difficult at best.

The tapered sides of the raised portion of the etched mold resulted in channels with tapered sides. To accommodate rectangular conductors, channels would have had to be embossed wider than the conductors by the amount of the taper. The consequences of this need were never fully resolved, as acceptable release from the etched surface was not obtained.

An attempt at fabricating a single channel mold by precision grinding was made but proved unsuccessful due to wear of the grinding wheel.

A multichannel mold was prepared at Langley Research Center by an Electric Discharge Machining process. The machined surfaces were smoother than those obtained by etching but not as smooth as desired. Test embossings were made with this mold which indicated that this process could yield useable embossed laminae. The mold was received too late to be fully evaluated, as an acceptable molding process had already been developed.

The embossing molds which were the most successful were made by alternately stacking thick and thin polished shims together. The top and bottom surfaces of the shims were ground parallel, in situ. The thin shims were then removed and the thick shims ground an additional 2-1/2 mils. Reassembling the thin shims in their original alternate locations formed the desired surface pattern. All surfaces of the mold in contact with a lamina were polished so that minimum adhesion was obtained. All laminates and arrays other than the single crossover laminates were made using this shim type of embossing mold. Molds for embossing 4 - 0.003 inch, 6 - 0.003 inch, 6 - 0.006 inch, 270 - 0.006 inch and 70 - 0.006 inch wide channels were made.

Acceptable release of laminae from the molds was obtained over a narrow range of temperature and pressure. At lower temperature and pressure incomplete embossing occurred. At higher temperature and pressure unacceptable release resulted. A range map for acceptable embossing is shown in Fig. 11.

6.2 Embedding of Conductors

After laminae are embossed, they are coated with a squeegee medium, L. Reusche and Co. Type 163C, scraped, and dried. Since this medium is over 90 percent pine oil, only a thin layer of resin is deposited in the bottom of the channels when the laminae are dried. This is used to cement the conductors in the channels during assembly.

The initial attempt at embedding a full complement of conductors did not use the coating of squeegee medium to secure the conductors. They were cemented into the channels with Santacizer 160, a Monsanto plasticizer, at two to four locations. As long as the Santicizer remained liquid, surface tension kept the conductors in their channels. However, when the plasticizer dried, the conductors would pop up. This embedding process worked for partially-populated arrays but not for the fully-populated arrays which required a longer time for insertion of the conductors and caused the Santicizer to dry out. The squeegee medium was therefore used.

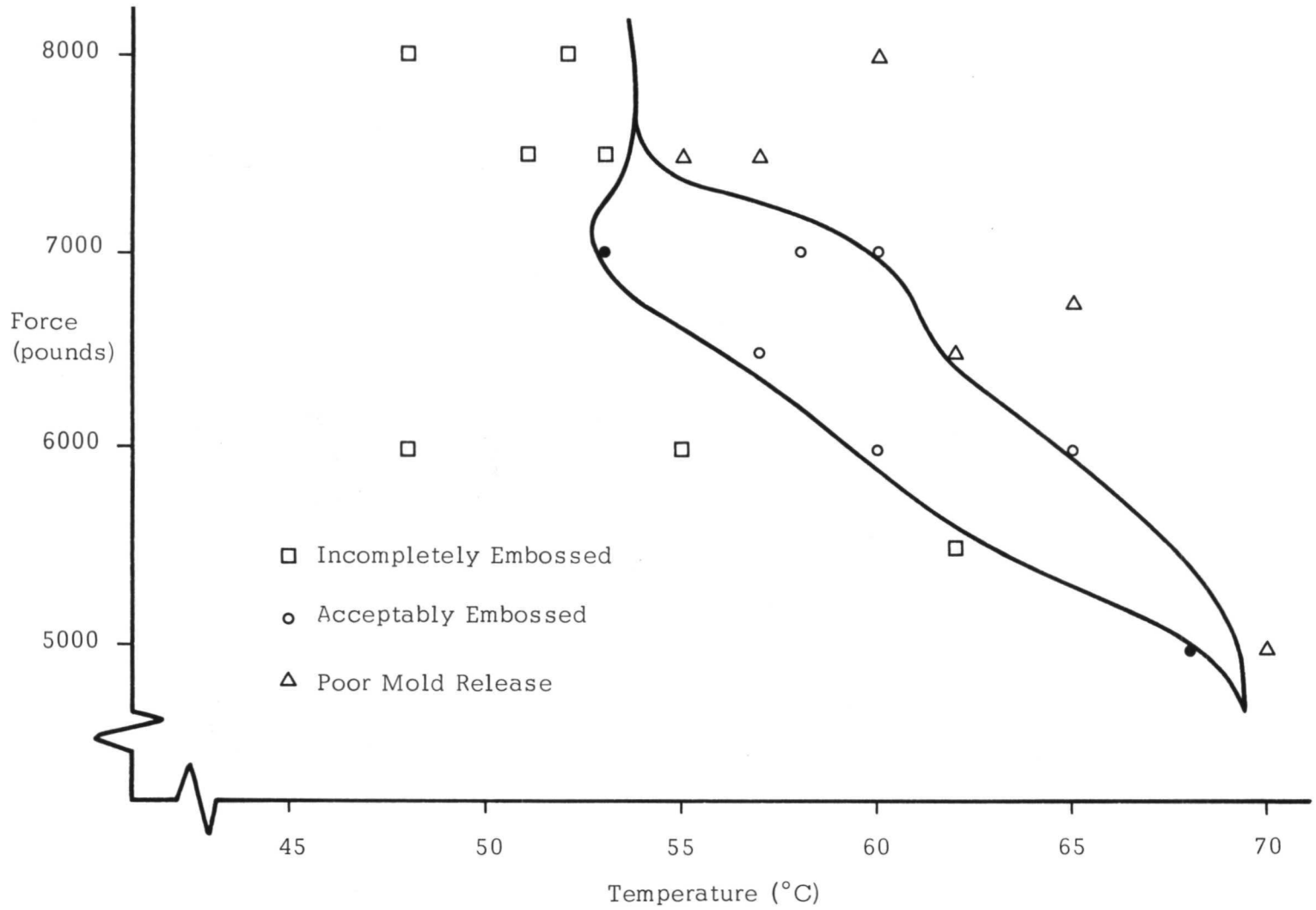

Fig. 11 Range Map for Laminae Embossing

Conductors were punched from bisque-fired conductor sheets and were measured for resistance to sort out defective conductors prior to their insertion in the channels. After insertion, the conductors were secured in place by thermobonding at a temperature of about 60°C under light pressure. When all the conductors were inserted in a lamina, the lamina was thermopressed between shims to embed the conductors so that they were flush with the surface of the lamina.

After the conductors had been pressed into the lamina, it was easily handled and could be bent without dislodging the conductors. In the early arrays the conductor width and channel width were made equal, which frequently caused a conductor to fit in the channel in a cocked position so that one conductor edge protruded above the top of the channel. This edge would penetrate into the insulating layer during bonding of the array and too often resulted in shorts. This cocking of the conductor was eliminated by making the conductors 0.0055 inches wide, providing approximately 0.0005 inch clearance.

6.3 Assembly of Laminae

The assembly of the laminae to form monolithic arrays was accomplished with the aid of a multisection assembly jig and a pair of trimming dies. After the embedding of a full complement of conductors in a word lamina and in a digit/sense lamina was completed, each lamina was trimmed to a size that would expose 0.050 inch at each end of the conductors. This was accomplished by making the digit/sense lamina 0.10 inch longer than the word lamina, the word lamina 0.10 inch wider than the digit/sense lamina, and the 0.0008 inch insulating lamina 0.1 inch less than the maximum length and width. The overall array dimensions were 4.159 inches x 1.160 inches before firing.

The assembly jig consisted of a base, two add-on alignment sections and a top. The add-on alignment sections controlled the positioning of the word lamina, the center lamina, and the digit-sense lamina, which were assembled in that order. After alignment of the three laminae, the top of the jig was added to maintain laminae alignment, and the add-on alignment sections were removed, to allow unrestricted vertical movement during the bonding step.

6.4 Bonding Laminae

Bonding of the laminae is accomplished by applying a pressure of 8 pounds per square inch at a temperature of 160°C to the assembled and aligned laminae for 1 hour. The oven is evacuated for the first 10 minutes to eliminate air entrapped between the laminae. Teflon sheets are used

between the alignment fixture and the laminae to prevent sticking of the array to the alignment fixture. Early laminates were bonded at 4 pounds per square inch. Memory test results indicated incomplete bonding at this pressure; therefore the bonding pressure was increased to correct this problem.

6.5 Firing of Arrays

The arrays were fired in a tube furnace at 1350°C for 4 hours in an oxygen atmosphere and cooled in nitrogen. This firing schedule differs from that used to obtain the characteristics listed in Table 7 for LM71 toroids in that the time at temperature was shortened to 4 hours from 24 hours. Test results obtained on partially-populated arrays fired with this shortened firing schedule gave good operating characteristics. Therefore the same firing conditions were maintained for the fully-populated arrays.

The firing schedule for the arrays also differed from that of the toroids in that the heating and cooling rates were controlled at 38°C per hour. This rate was sufficiently slow to accomplish the burnoff of the binder during the heating cycle.

For the firing of the arrays, each was placed on an alumina setter which was covered with a coating of thoria powder to prevent sticking of the array to the setter. A second alumina setter was supported over the top of the array by a pair of spacers to keep it from resting on the array.

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7.0 TESTING

The tests performed in the first phase were on toroidal samples to evaluate the compositions and the effects of the firing treatments. The static characteristics such as coercive force, flux density, resistivity, grain size, and Curie temperature were measured by standard techniques. When the static characteristics for a given composition and firing treatment approached the target values, dynamic tests were also performed. These tests included the determination of switching constant, partial set state thresholds, and memory tests using the test program shown in Fig. 12. These tests suffered in interpretation, due to the differences in the flux paths switched in a toroid and in a monolithic array, but produced as close to array type operation as was possible with a structure of simple geometry.

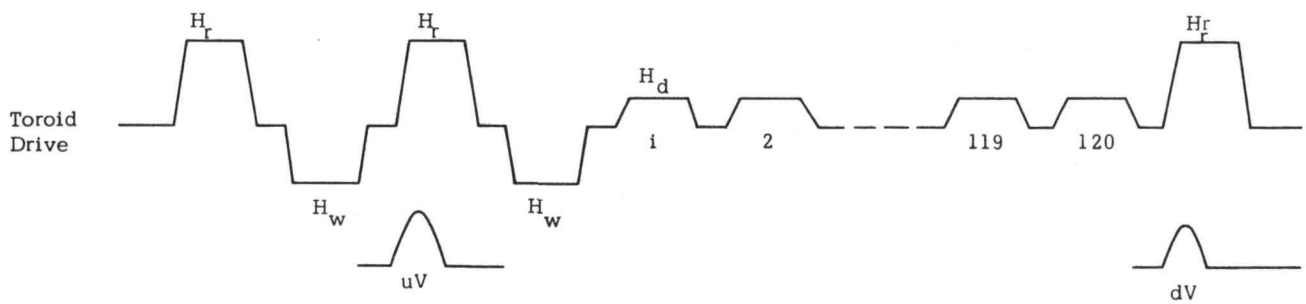

Fig. 12 Toroid Test Program

Memory testing of the monolithic arrays fabricated in Phase II was performed using the two-crossover-per-bit configuration. Two array test programs were used to evaluate memory performance. The major feature of these tests was a pattern of 120 digit pulses used to disturb each memory cell before readout to obtain the dV_o, dV_1, D_{so}, and D_{s1} disturb signals. All pulse tests were conducted using Hewlett Packard 214A pulse drivers having a $<$ 15 nanosecond rise and fall time and 50 ohm source impedance.

7.1 Material Evaluation

The characteristics of twenty six compositions prepared in the first phase were evaluated by various dynamic and static tests. For the static tests, B-H loops were used to determine the coercive force, remanent flux density, and squareness. B-H loops of the four recommended materials are shown in Figs. 13 through 16. Grain size determinations were made from photomicrographs of polished and etched disc samples using the line intercept method. A photomicrograph of a LM-71-B-4 sample is shown in Fig. 17. Resistivity measurements were made on disc samples using conductive epoxy electrodes to make contact with the top and bottom surfaces. Curie temperature was determined by two methods: the vibrating sample magnetometer method and a B-H loop method. In the vibrating sample method the $4\pi M_s$ was plotted as a function of temperature. The Curie temperature is obtained from this graph by the empirical method of extrapolating the curve to $4\pi M_s = 0$, disregarding the inflection in the curve at low values of $4\pi M_s$ due to interaction between the orienting field and the saturation magnetization moment.[1] Fig. 18 shows the $4\pi M_s$ vs T relationship for a LM-84-1 sample. In the B-H loop method, the Curie temperature was determined by heating toroidal samples and noting the temperature at which the B-H loop degenerated to form a linear relation between B and H.

For the dynamic tests, the switching constant was determined for switching times between 0.1 to 1 microseconds. The switching constant curve for a LM-86-1 sample is shown in Fig. 19. Profile characteristic curves[2] were taken to determine the threshold variation when a core was partially switched. A profile curve is shown in Fig. 20 for a LM-86-1 sample. Memory tests were performed using test patterns that disturb a

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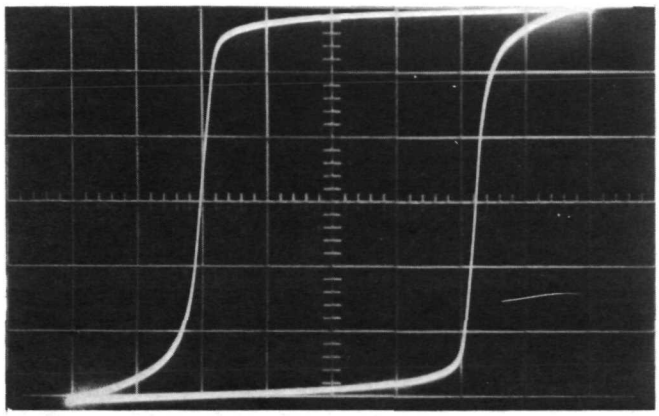
[1] Bozorth, B.M., Ferromagnetism, Van Nostrand, 1954, ff713.

[2] Heckler, C.H., "Development of a Toroid Having Unique Partial-Switching Characteristics and Fabrication of an Integrated Magnetic Logic Structure," Contract NAS1-5963 NASA CR-66496, October 1967.



Vert = 275 gauss/cm
Hor - 0.31 Oe/cm

Fig. 13 B-H Loop of LM-71-B-4

Vert = 275 gauss/cm
Hor = 0.32 Oe/cm

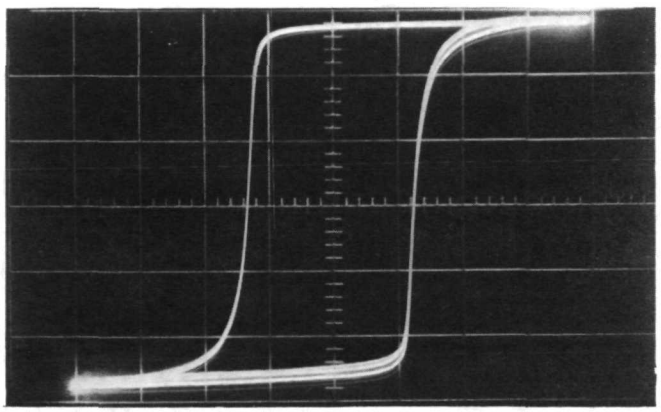


Fig. 14 B-H Loop of LM-84-1

Vert = 285 gauss/cm
Hor = 0.32 Oe/cm

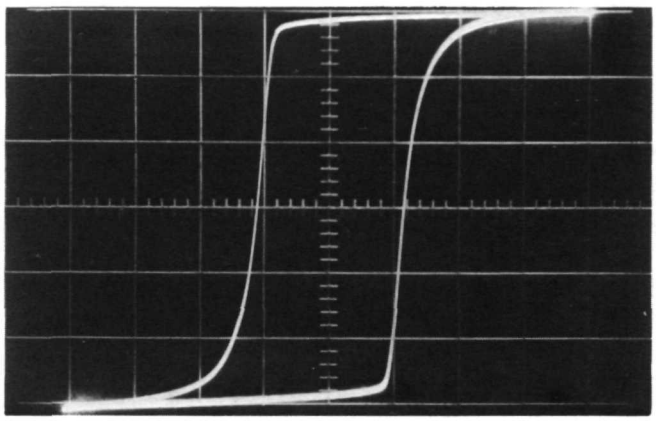
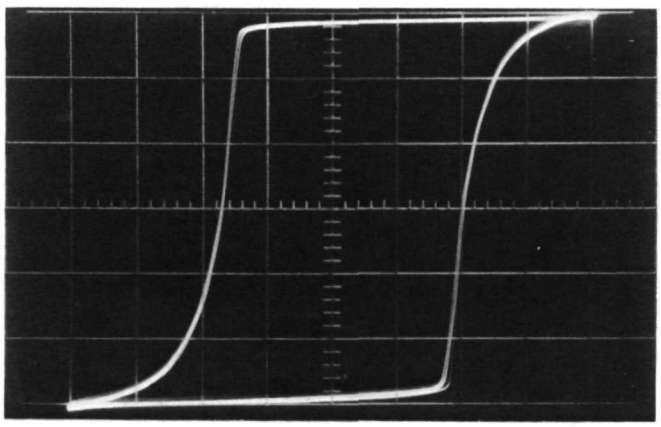


Fig. 15 B-H Loop of LM-85-1



Vert = 220 gauss/cm
Hor = 0.32 Oe/cm

Fig. 16 B-H Loop of LM-86-1

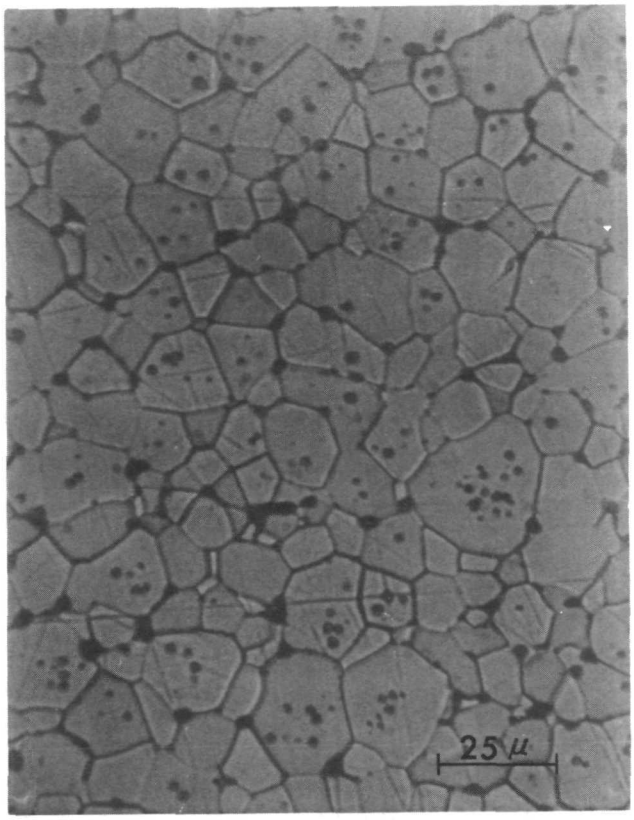


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Fig. 17 Photomicrograph of LM-71-B-4

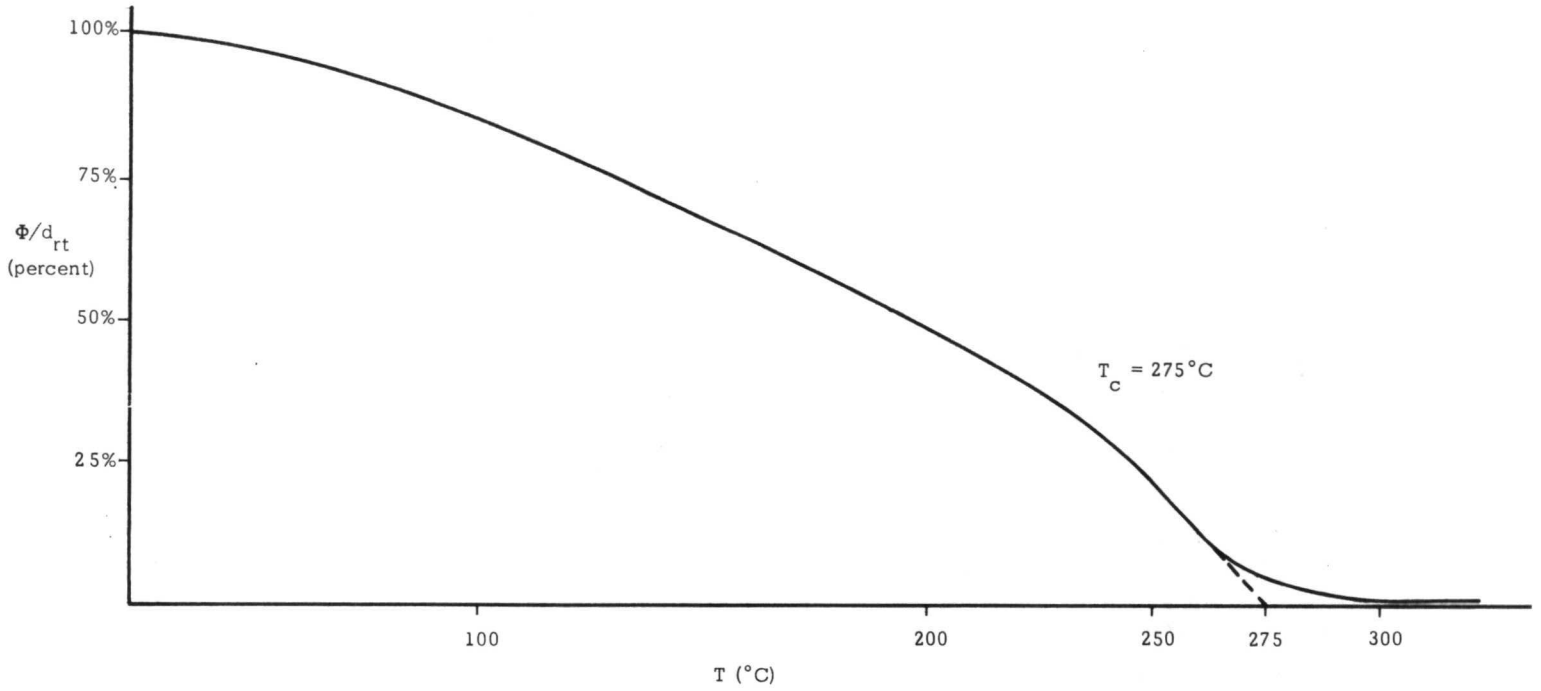


Fig. 18 Variation of $4\pi M_s$ as a Function of Temperature for LM-84-1

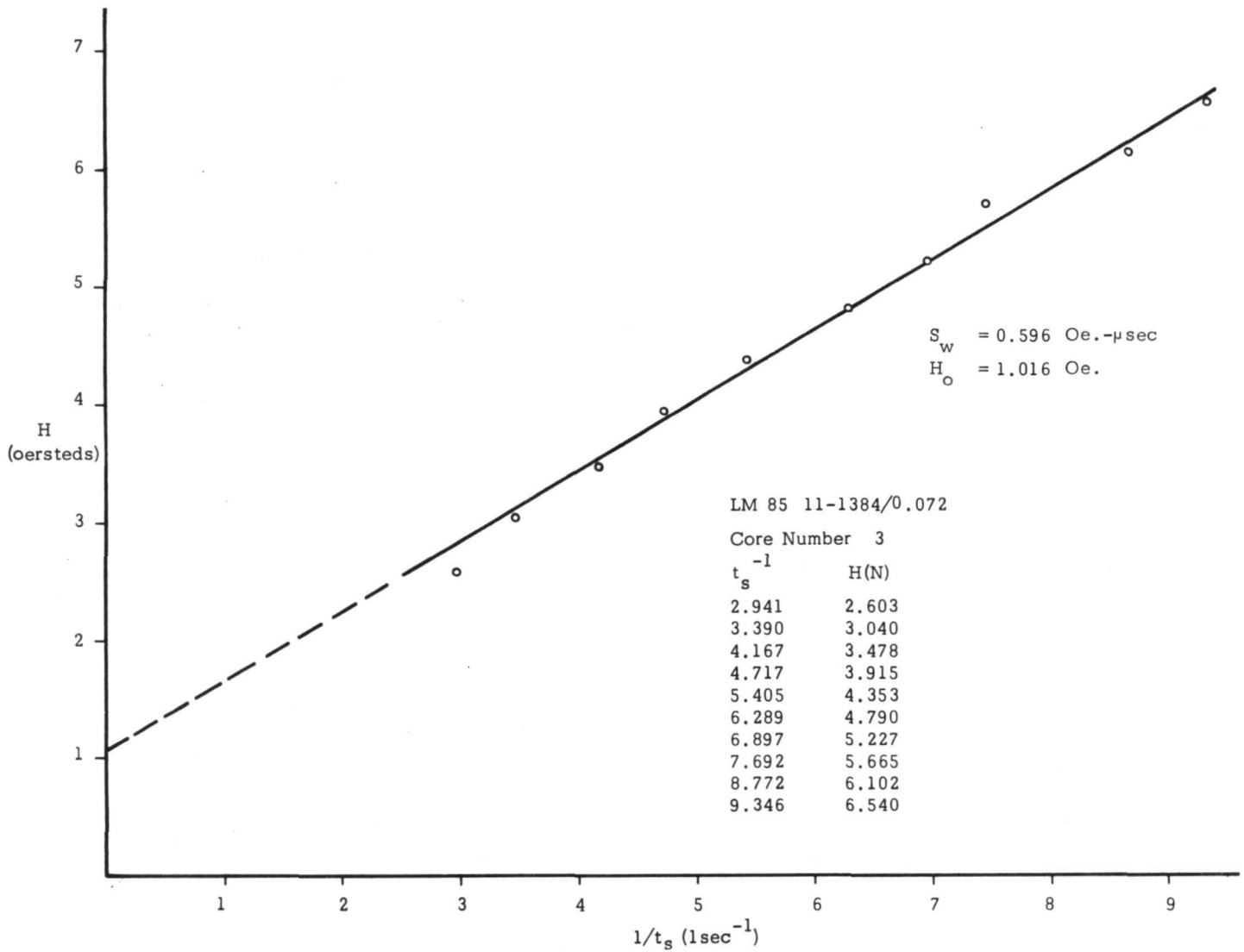


Fig. 19 Switching Characteristic Curve for LM-85-1

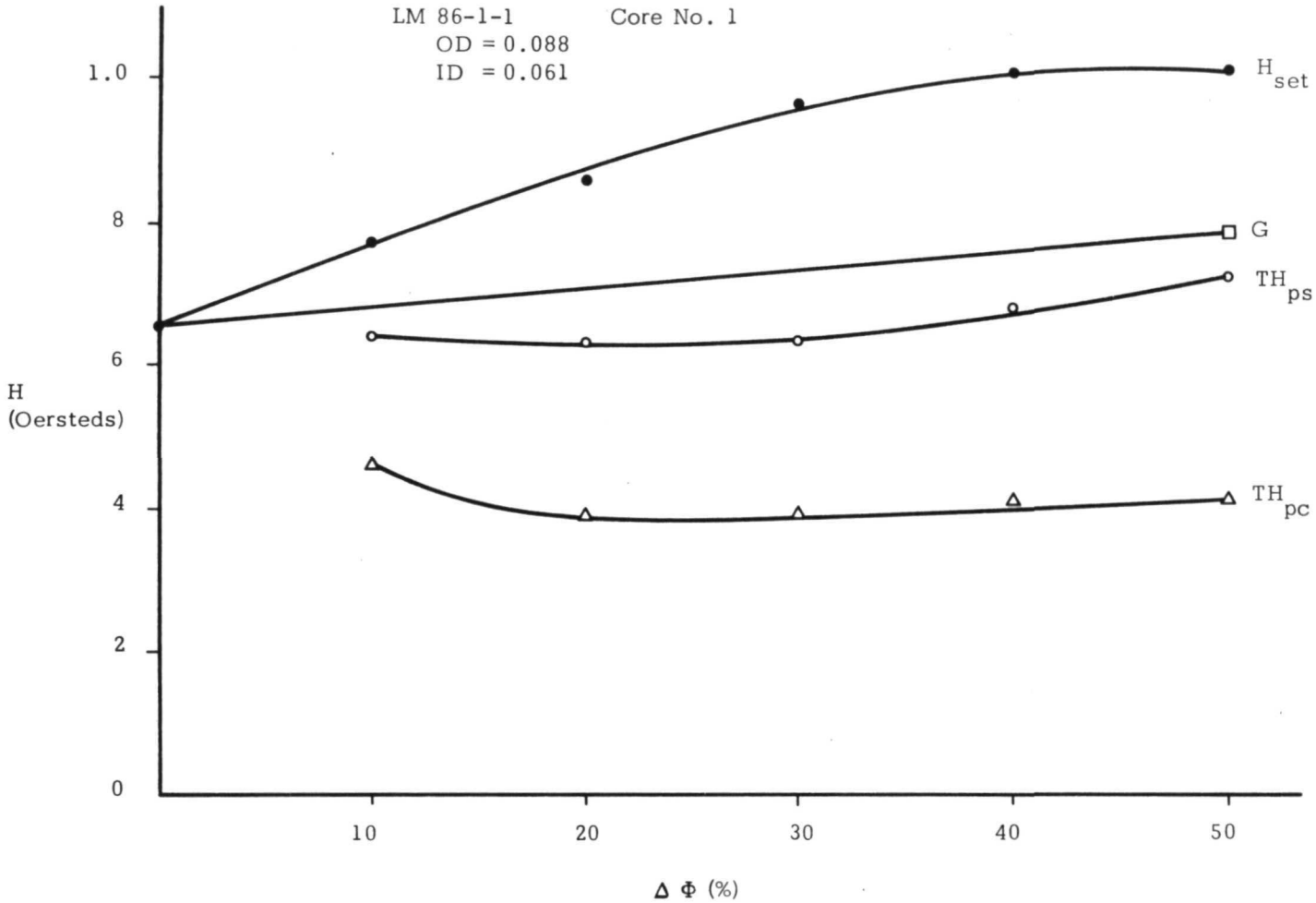


Fig. 20 Profile of Partial Set State Thresholds for LM-8601 Toroidal Samples

stored bit 120 times before readout. In these tests the undisturbed (uV) and disturbed (dV) signal outputs were measured for drive currents determined by the formula given in Table 9 for switching times of 1.0, 0.5, and 0.2 μsec.

The minimum ratio of uV/dV occurred for a switching time of 0.5 μsec as shown for several samples in Table 10. For this reason the majority of the memory tests were made for the 0.5 μsec switching time. Two core sizes, 300/330 and 70/100, were used to determine if the size of the core tested affected the uV/dV ratio. Variations did occur, but a pattern was not discernible.

To obtain an estimate of the disturb sensitivity of the materials, the value of the postwrite disturb current to give a uV/dV ratio of 1.3 was determined. The original target objective had been to obtain a uV/dV ratio of 1.3 for a disturb current pulse amplitude equal to the digit current pulse amplitude. The materials tested had considerably higher ratios. Therefore this alternate measurement was introduced to evaluate the disturb sensitivity. Table 11 shows the results of the dynamic tests on samples of the four recommended compositions. The values of uV/dV listed in this table are for t_s = .5 μsec and 70/100 size cores.

7.2 Array Evaluation

The monolithic arrays were tested in a two-crossover-per-bit configuration. The test patterns used for determining the undisturbed signal (uV) and the disturbed signal (dV) outputs are shown in Fig. 21. The additional test pattern shown in Fig. 22 was used to determine the magnitude of the unbalance signal and the signal induced by digit pulses alone.

The test setup for the array tests is shown diagrammatically in Fig. 23. The program logic was built from data technology logic cards. Two crossover-per-bit operation was obtained using only 4 drivers: write, read, ZERO digit and ONE digit. In this balanced drive arrangement, the two conductors of each digit-sense pair are connected together at one end to provide the oppositely-directed digit currents for each conductor. The drivers are Hewlett-Packard 214A pulse generators with rise and fall times of less than 15 nsec. The sense signals are developed across the 330 ohm impedance-matching resistors and differentially connected to the type W plug-in of the Tektronix 547 oscilloscope to eliminate the common mode noise signal. The arrays are mounted on a PC board with a copper-ground plane for minimization of the differential noise signal. The connection between the array and the scope input is by 300 ohm shielded cable. On one side of the array the word conductors are connected together and to the ground plane. The read and write drivers are connected to the selected word conductor through a 36 ohm resistor. The conductor lines in the first arrays

Table 9 Drive Current Specifications for Memory Testing of Toroidal Cores

	Amplitude (Oe)	Width (μsec)	Rise and Fall Times (nsec)
H_r	$s_s/t_{sw} + H_c$	$2.5\ t_{sw}$	<15
H_w	$s_s/t_{sw} + H_c$	$.9\ t_{sw}$	<15
H_d	H_c	$2.0\ t_{sw}$	<15

Table 10 Memory Test Data for Recommended Compositions

Material	Core No.	Core Dia. (inches)	H_c (Oe)	s_w (Oe-μ sec)	t_s (μsec)	I_d (ma)	I_{d1} for uV/dV = 1.3 (ma)	uV/dV
LM 71-B-4	1409/1	0.328	0.622	0.507	1.0	0.308	0.210	4.0
					0.5	0.308	0.206	3.0
					0.2	0.308	0.188	3.0
LM 71-B-4	1409/3	0.092	0.604	0.573	1.0	0.150	0.116	2.7
					0.5	0.150	0.116	2.2
					0.2	0.150	0.110	2.5
LM 71-D-3	1409/3	0.092	0.595	0.590	1.0	0.149	0.108	2.9
					0.5	0.149	0.104	2.5
					0.2	0.149	0.098	3.0
LM 71-5-1	1396/3	0.092	0.777	0.594	1.0	0.227	0.081	4.3
					0.5	0.227	0.102	3.2
					0.2	0.227	0.099	4.0

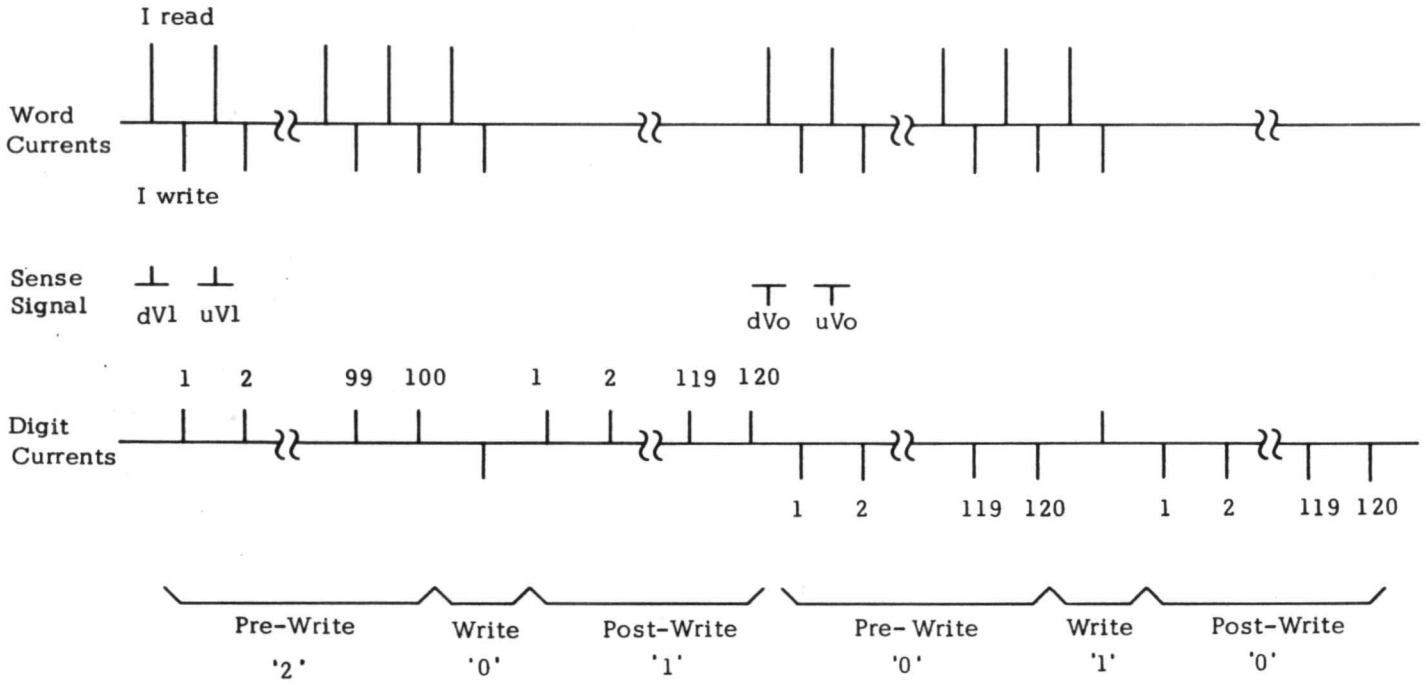


Fig. 21 Array Test Program 1

Table 11 Dynamic Characteristics of Recommended Materials

Material	Firing			s_w	H_o	uV/dV	H_{dr} for uV/dV = 1.3	H_{dr}/H_c
	Temp (°C)	Time (Hours)	Atmosphere (Heat-soak-cool)	(Oe-μ sec)	(Oe)	-	(Oe)	
LM 71-B-4	1350	24	O_2/N_2	0.50	1.54	4.3	0.43	0.64
LM 84-1-2	1350	24	O_2/N_2	0.53	1.49	3.0	0.21	0.50
LM 85-1	1350	24	O_2/N_2	0.52	1.43	5.0	0.35	0.63
LM 86-1	1325	4	O_2/N_2	0.53	1.94	3.2	0.31	0.51

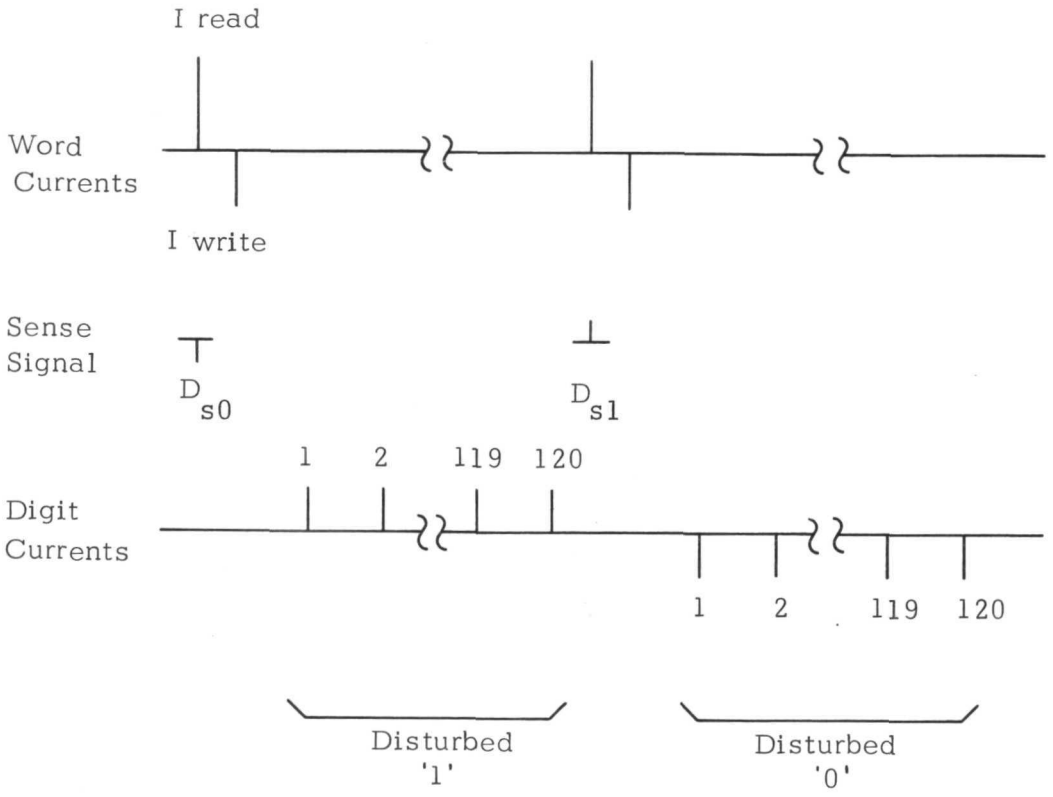


Fig. 22 Array Test Program 2

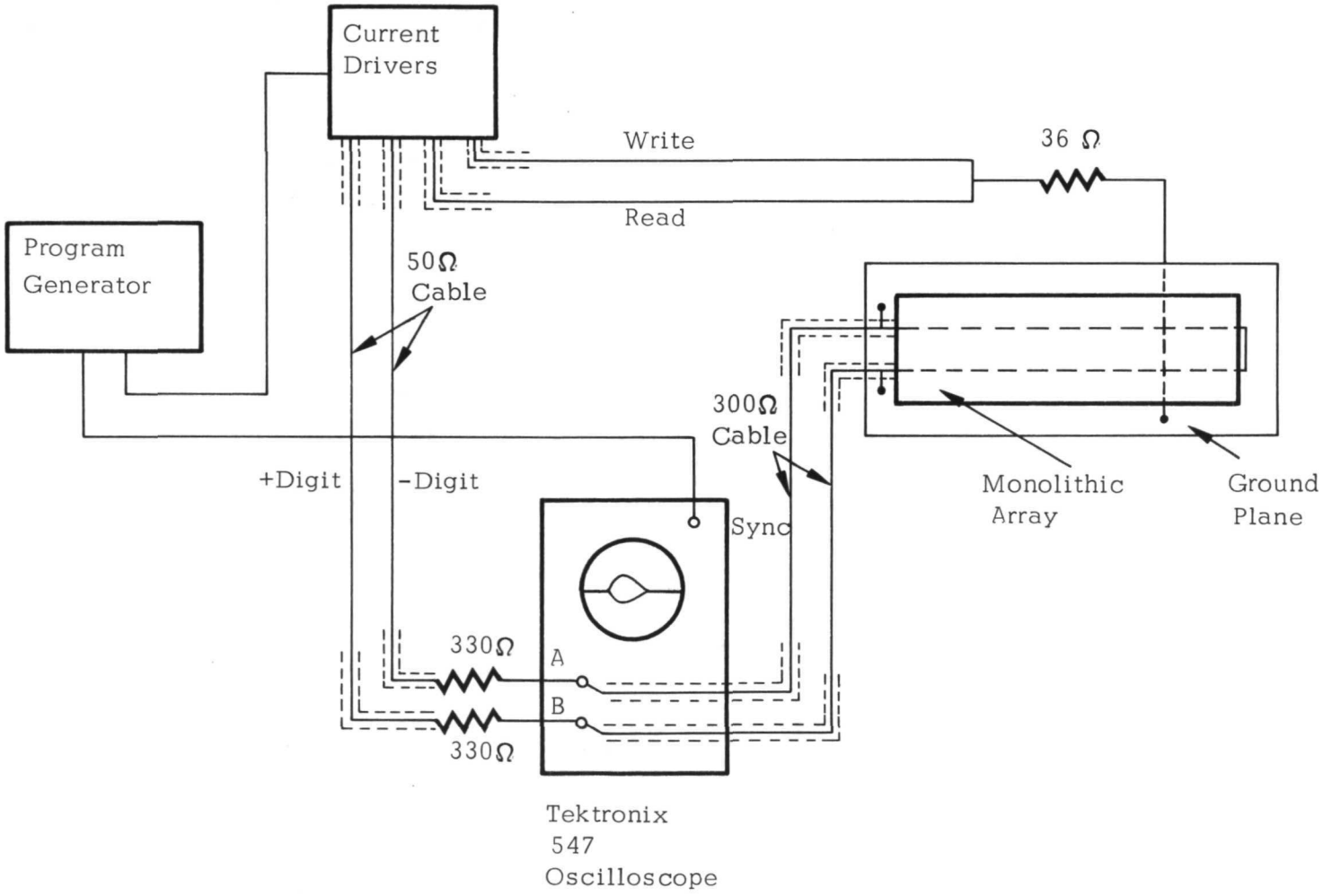


Fig. 23 Array Test Setup

were 1.7 x 2.4 mils and had a resistance of 5 ohms per inch. To decrease the resistance to the target value of 3 ohms per inch, the conductors were widened to be 0.004 inches when fired. A photomicrograph showing a cross section of the embedded conductors is shown in Fig. 24.

The initial tests on the partially populated arrays gave sense output signals of nearly 3 millivolts at the drive conditions given in Table 12. These standard test conditions were used for all array tests. The uV and dV signals for a ONE and ZERO are shown in Fig. 25. The 6 partially-populated and 8 fully-populated arrays successfully fabricated are listed in Table 13.

An x-radiograph showing the embedded conductors in a fully-populated array is shown in Fig. 26. Fig. 27 shows the dV_1 and dV_0 sense signals for maximum signal and minimum signal bit storage locations in array MA9. Histograms of the signal levels of two 100% tested arrays are shown in Figs. 28 and 29. The variation in sense signal with variation in the drive currents and write current pulse width was determined by varying the drive conditions on only one drive pulse, keeping the others at the standard test values. Graphs showing these variations of the disturbed sense signal are shown in Fig. 30 for both peak voltage and flux. The peak voltage varies nearly linearly with read current, with a slope of 40 μvolts per milliamp. The graphs for the variation of the peak voltage as a function of write current, write-pulse width, and digit current all show a maximum value at the standard test conditions. The graphs for the variation in flux also show a maximum value, except for the write-pulse width which would reach a maximum off scale, but at currents greater than the standard test currents. The sense signals for the 12th bit of the 123rd word in array MA8 are shown in Fig. 31 for standard test conditions and in Fig. 32 for increased currents as listed in Table 14.

The signal attenuation, delay, capacitance per crossover, and inductance per crossover that were measured on a partially populated array are given in Table 15 which summarizes the characteristics of the monolithic memory arrays.

Table 12 Drive Conditions for Array Evaluation

	Current Amplitude (ma)	Pulse Width (μsec)	Rise/Fall Time (nsec)
I_{write}	70	0.4	< 15
I_{read}	100	1.0	< 15
I_{digit}	18	0.6	< 15

Table 13 Identification of Fabricated Monolithic Memory Arrays

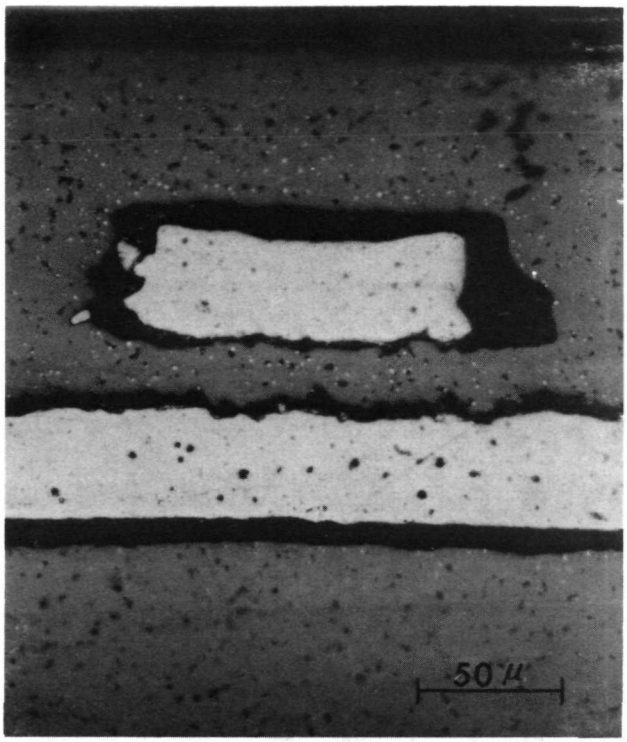
Firing No.	Array No.	No. of Conductors Digit	Sense	Word	Conductor Size (mils)	Conductor Resistance (Ohms/in)	Sense Sig. uV/dV (m volts)	Remarks
2483	1	4	x	12	3	-	-	
2471	1	4	x	15	3	7.4 - 7.8	-	
2471	2	4	x	8	3	-	-	
2502	1	12	x	12	6	2.4 - 2.9	5/2.0	
2502	2	12	x	12	6	2.3 - 3.0	4.5/1.0	
2513	1	8	x	12	6	2.4 - 2.6	-	
2513	2	8	x	12	6	2.6 - 2.9	-	
2524	1	8	x	12	6	2.7 - 3.0	7/2.8	
2524	2	8	x	12	6	2.6 - 3.5	7/2.8	
2557	1	8	x	12	5	3.0 - 4.0	7.5/2.2	
2557	2	8	x	12	5	-	6/2.2	
2600	1	8	x	12	5	-	-	Severely cracked
2600	2	8	x	12	5	3.0 - 3.6	7/2.1	Fully embossed
2656	1	8	x	12	5	-	-	Fully embossed
2711	MA3	70	x	270	5	-	-	
2777	MA4	70	x	270	5	3.3 - 4.2	-	
2899	MA5	70	x	270	5	2.7 - 2.8	3.0/1.5	
2813	MA6	70	x	270	5	-	-	
2846	MA7	70	x	270	5	-	-	
2860	MA8	70	x	270	5	2.3 - 2.6	4.5/1.6	
2873	MA9	70	x	270	5	2.6 - 2.8	4.5/1.5	
2886	MA10	70	x	270	5	2.4 - 2.6	4.5/1.5	
2897	MA11	70	x	270	5	2.1 - 2.5	4.5/1.2	

Table 14 Current Conditions for Sense Signals of Figure 32

	Current Amplitude (ma)	Pulse Width (μsec)	Rise/Fall Time (nsec)
I_{write}	100	.45	< 15
I_{read}	130	1.0	< 15
I_{digit}	18	.6	< 15

Table 15 Electrical Characteristics of Monolithic Arrays

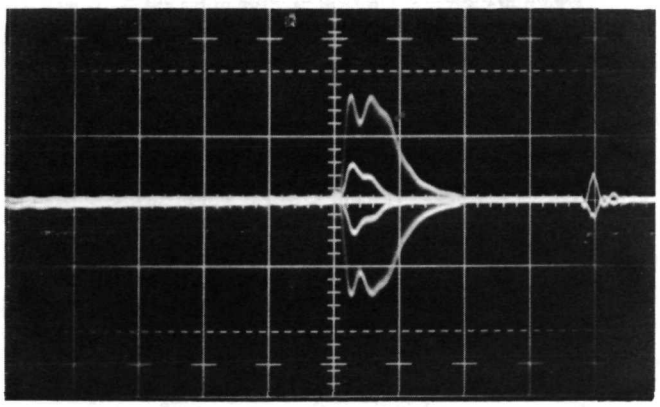
Word conductor resistance	3.0 Ω sq. in.
Digit-sense conductor	2.72 Ω sq. in.
Coupling resistance	10^7 Ω
Distributed inductance per crossover	2.31 nanohenries
Distributed capacitance per crossover	.26 picofarads
Digit-sense line attenuation/crossover	1.31×10^{-3} dB
Digit-sense line delay per crossover	37 picoseconds
uV/dV	2.5 - 2.9
$D_s D_v$	.41 - .63
Disturbed signal flux:	
Standard test conditions	0.02 maxwells
Test condition of Table 14	0.09 maxwells



400 X

Fig. 24 Cross Section of Embedded Pt-Alloy Conductors

uV = 7.0 mV
dV = 2.8 mV



Vert = 5.0 mV/Div
Hor = 0.25 μsec/ Div.

Drive Currents:
T_w = 0.45 μsec
I_w = 70 mA
I_R = 70 mA
I_D = 18 mA

Fig. 25 Sense Signals from Partially Populated Array
F 2524/2

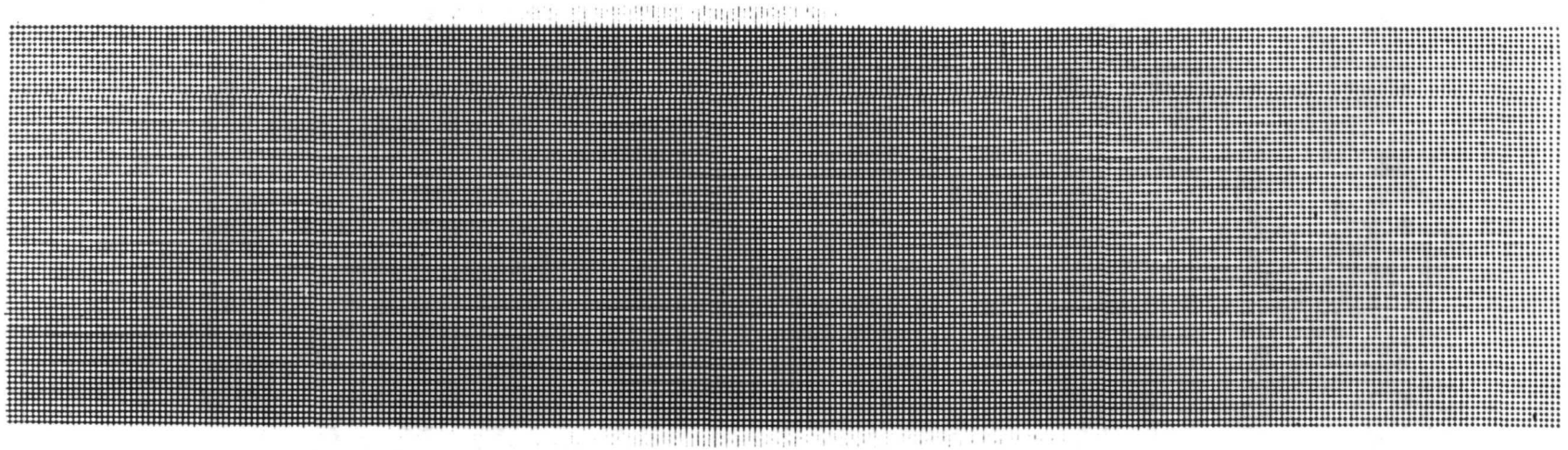
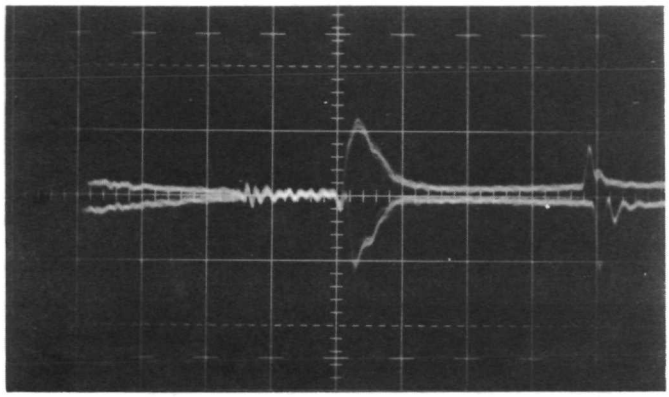


Fig. 26 X-Radiogram of Conductors in Array MA 8

Vert 1 mV/Div
Hor .25 μsec/
Div

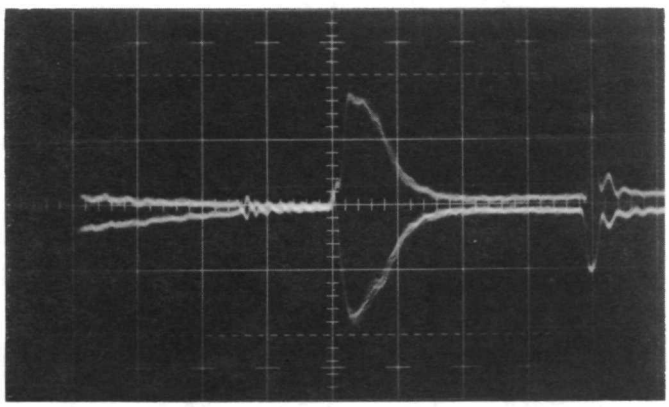


Digit 35
Word 111
Array MA9

Drive Currents:

T_w = 0.45 μsec
I_w = 70 mA
I_R = 100 mA
I_D = 18 mA

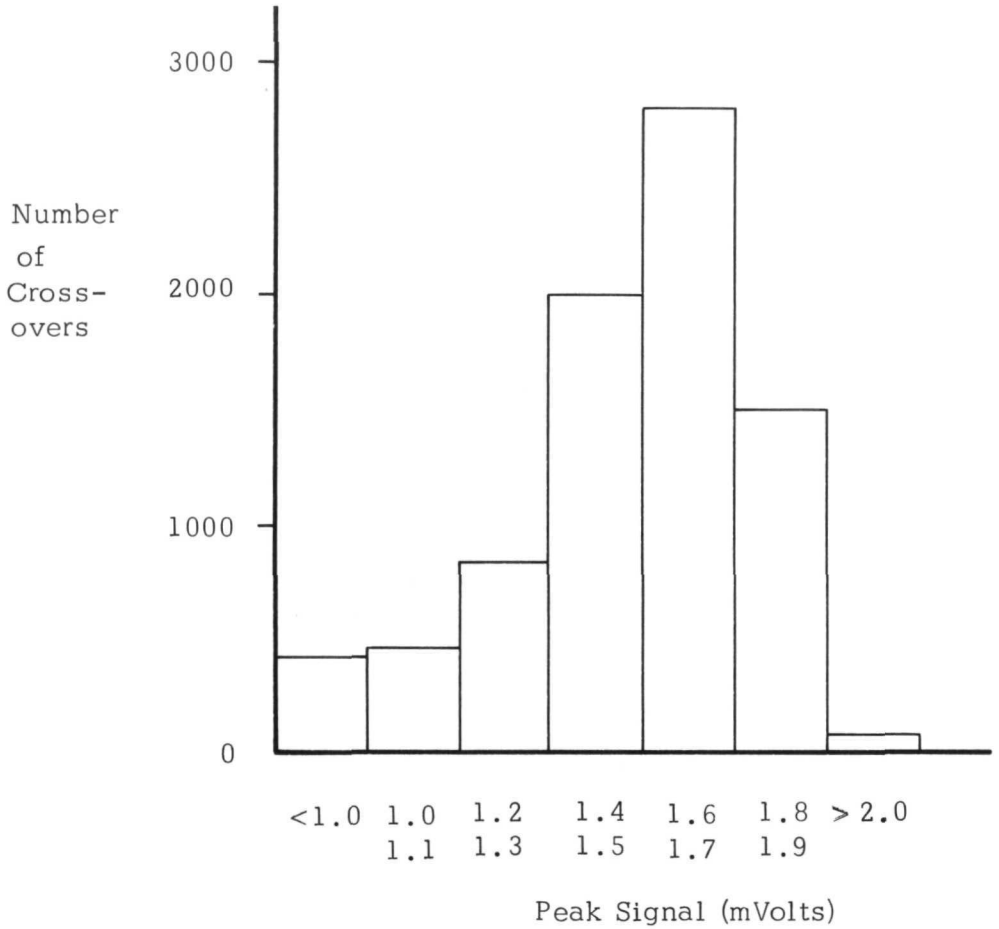
Vert 1 mV/Div
Hor .25 μsec
Div



Digit 15
Word 113
Array MA9

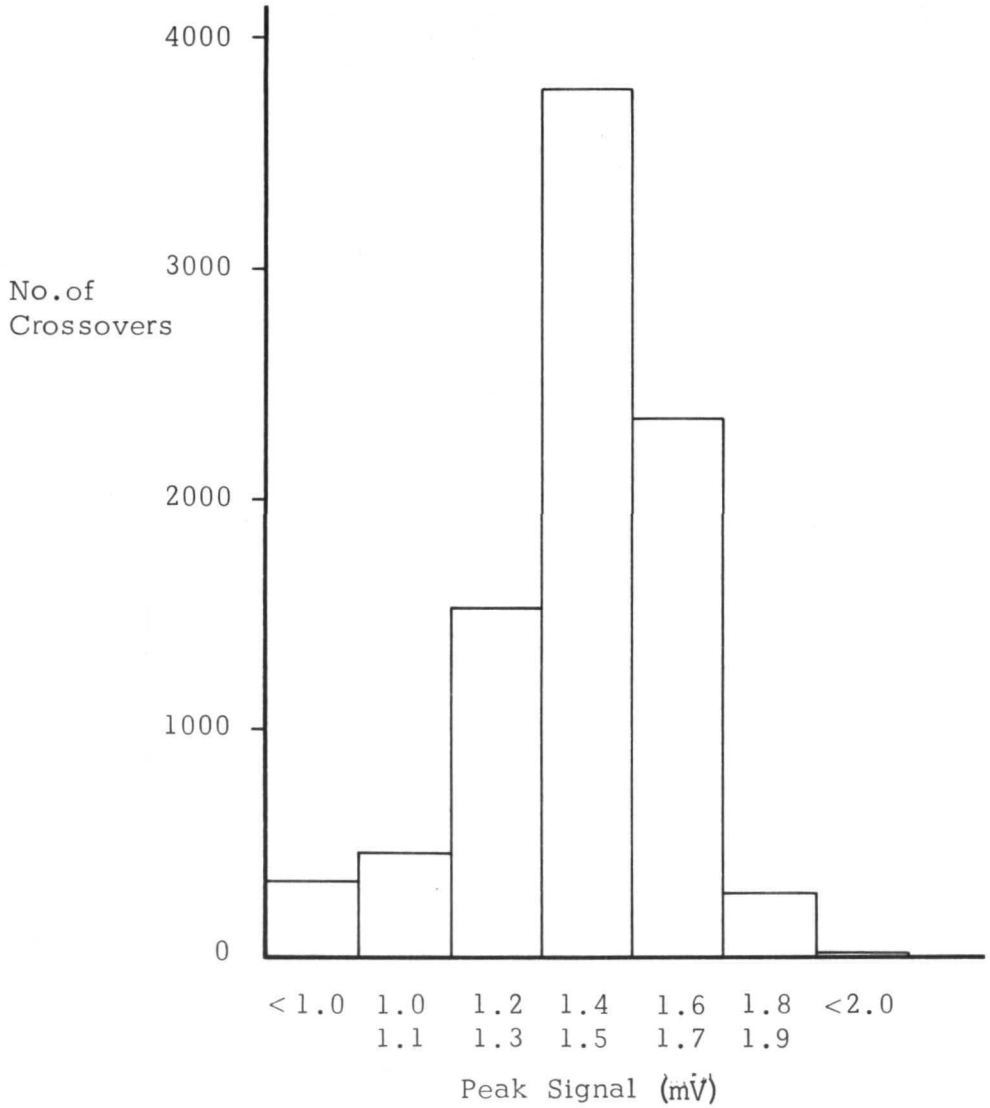
Drive Currents:
T_w = 0.45 μsec
I_w = 70 mA
I_R = 100 mA
I_D = 18 mA

Fig. 27 Minimum and Maximum Disturbed Sense Signals of Array MA9



Peak Signal (mV)	No. of Cross-overs
< 1.0	434
1.0, 1.1	441
1.2, 1.3	828
1.4, 1.5	1986
1.6, 1.7	2829
1.8, 1.9	1524
> 2.0	118

Fig. 28 Histogram of Signal Levels in Array MA 8



Peak Signal (mV)	No. of Crossovers
< 1.0	374
1.0 , 1.1	477
1.2, 1.3	1565
1.4, 1.5	3772
1.6, 1.7	2345
1.8, 1.9	312
< 2.0	4

Fig. 29 Histogram of Sense Signal Levels for MA9

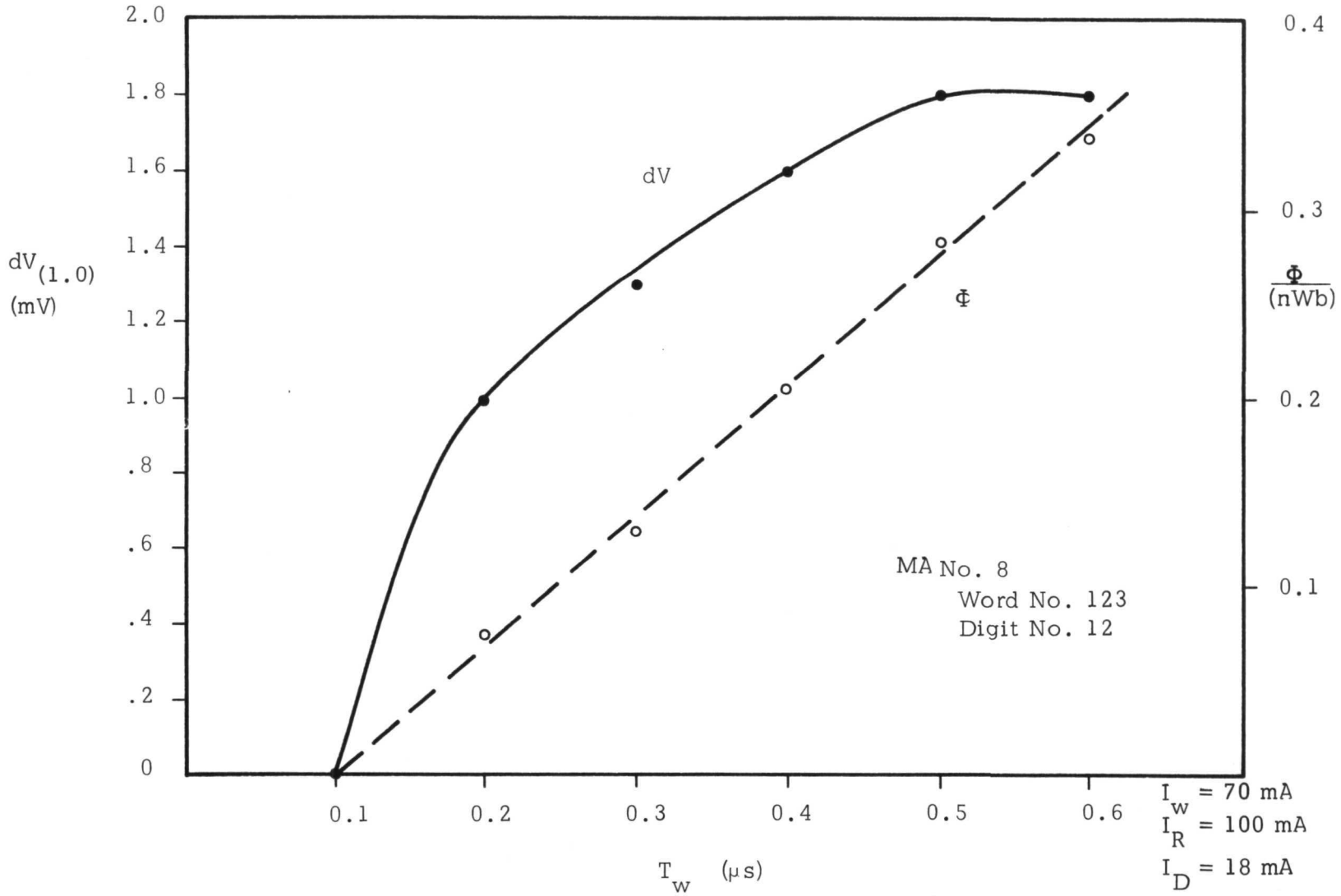


Fig. 30a Variation of Sense Signals as a Function of T_w

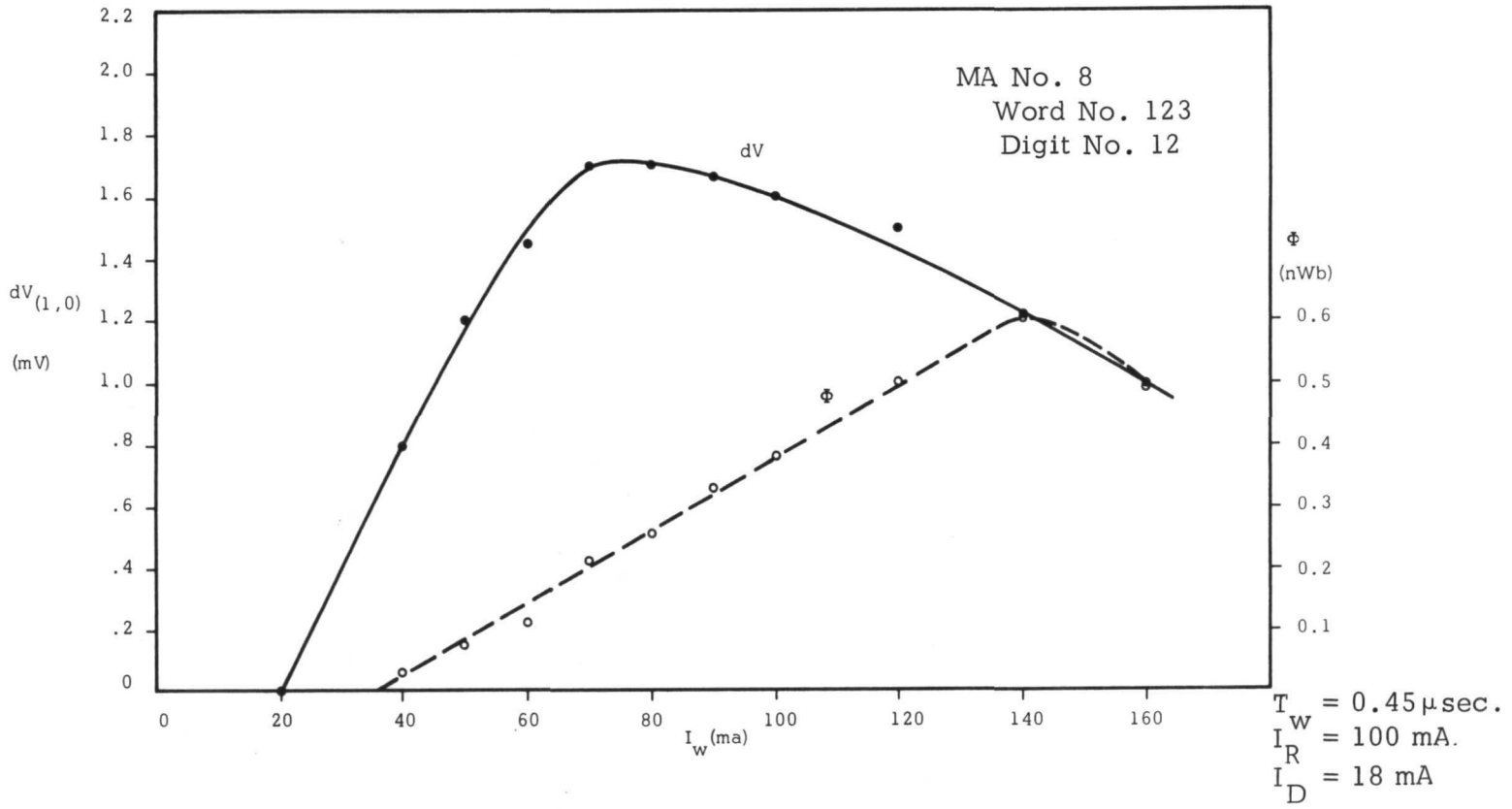


Fig. 30b Variation of Sense Signals as a Function of I_w

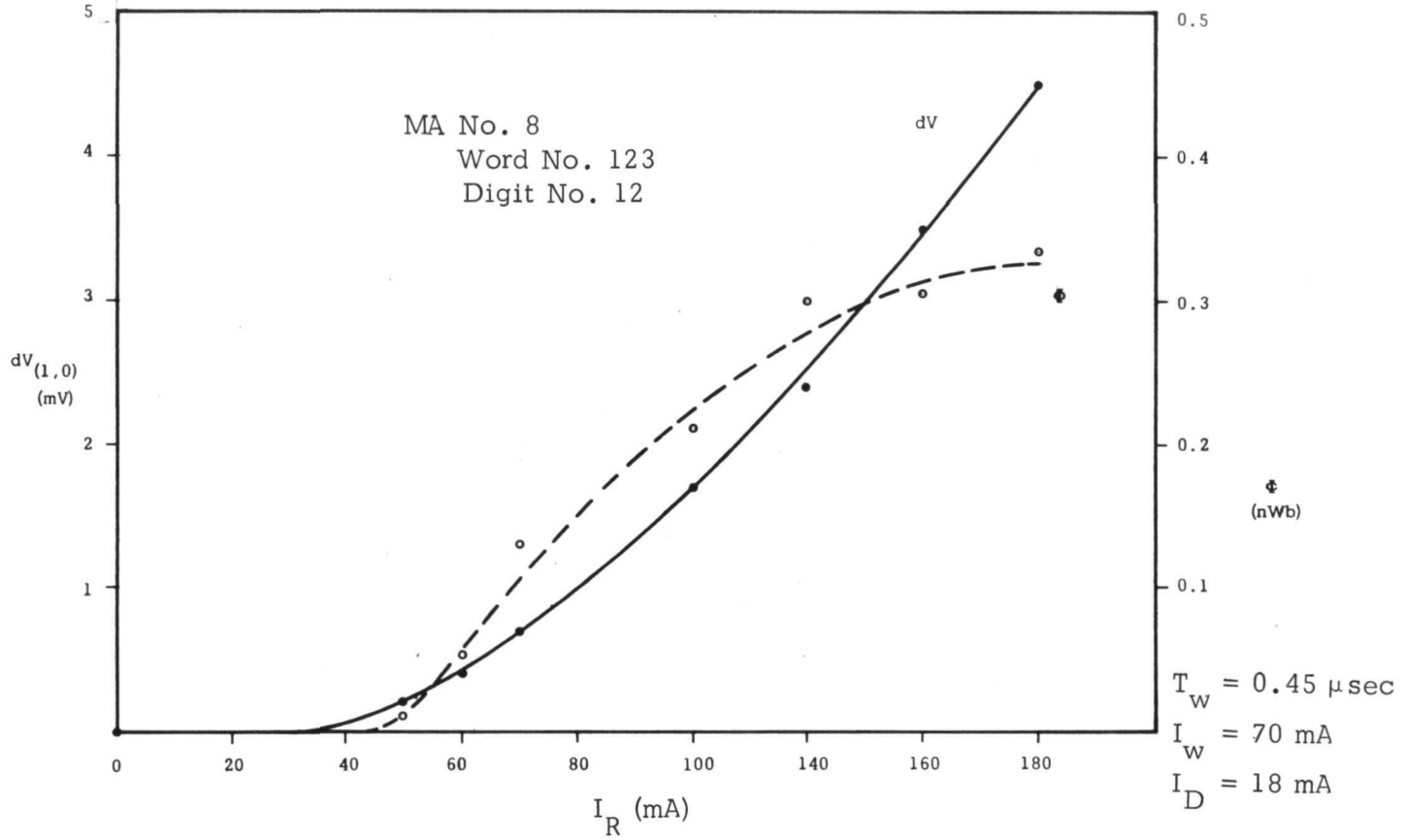


Fig. 30c Variation of Sense Signals as a Function of I_R

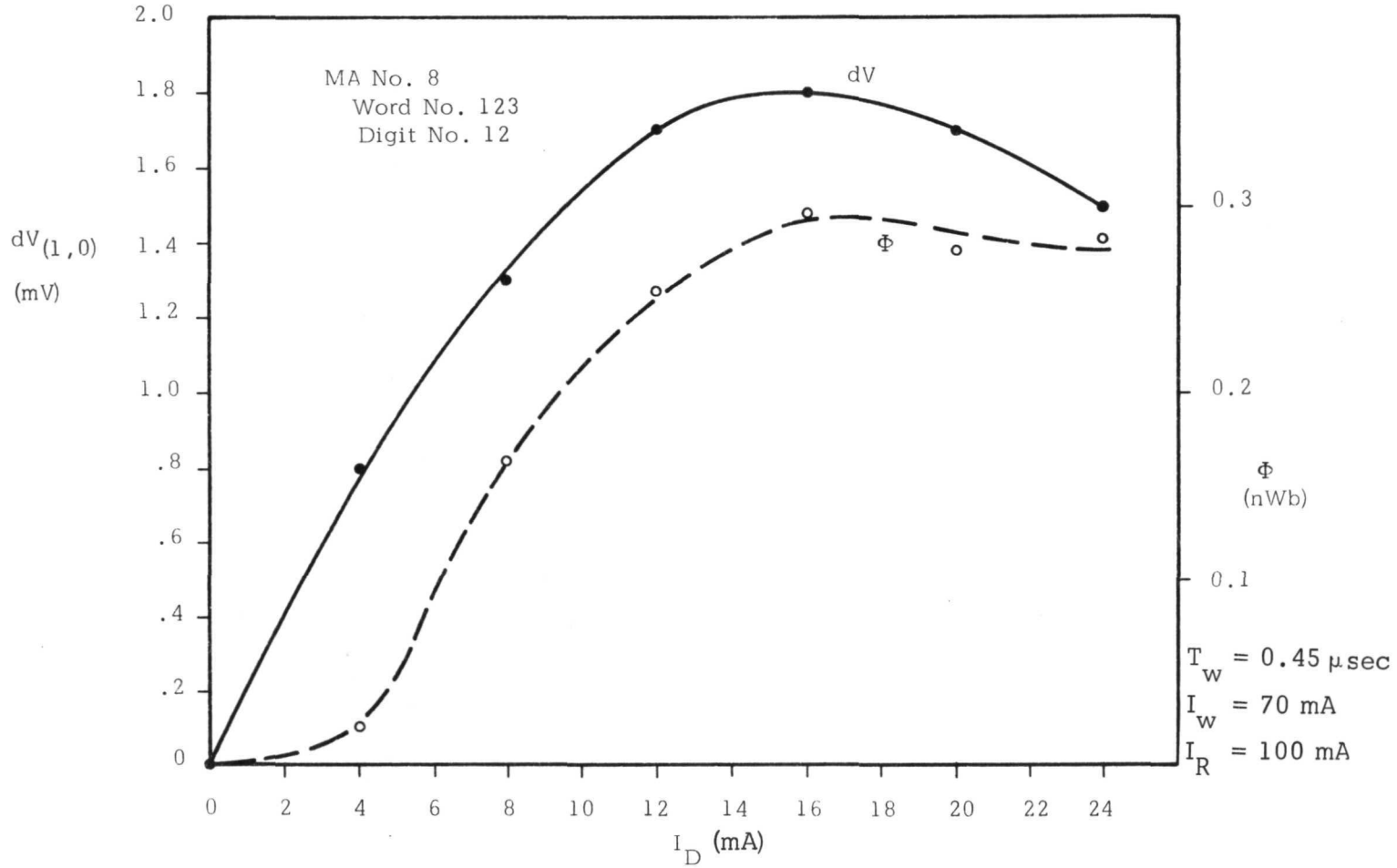
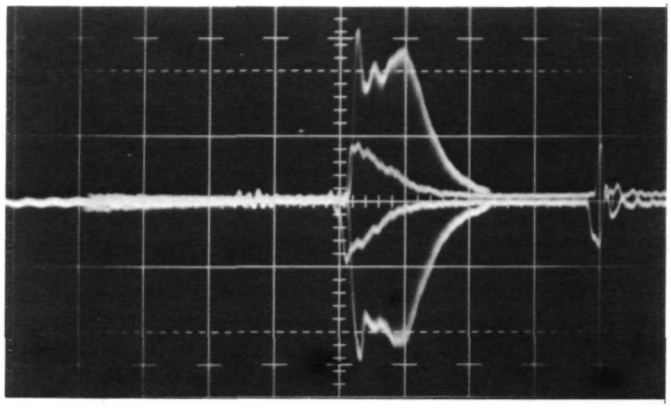


Fig. 30d Variation of Sense Signals as a Function of I_D

uV = 4.5 mV
dV = 1.7 mV

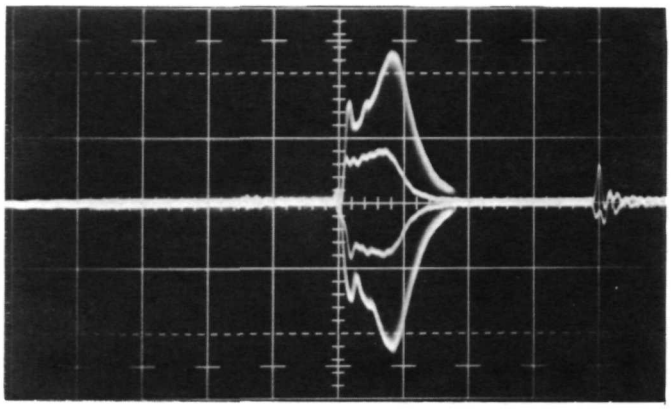


Vert = 2 mV/Div
Hor = 0.25 μsec/Div

T_w = 0.4 μsec
I_w = 70 mA
I_R = 100 mA
I_D = 18 mA

Fig. 31 Sense Signal for Standard Test Conditions of Bit 12, Word 123, Array MA8

uV = 11.5 mV
dV = 4 mV



Vert = 5 mV/Div
Hor = 0.25 μsec/Div

T_w = 0.45 μsec
I_w = 100 mA
I_R = 130 mA
I_D = 18 mA

Fig. 32 Sense Signal for Increased Drive Currents of Bit 12, Word 123, Array MA8

8.0 CONCLUSIONS AND RECOMMENDATIONS

The development of ferrite monolithic memory arrays has required the synthesis of a material having special magnetic and physical characteristics and the development of processes: for making flexible sheets of this composition, for embedding conductors in ferrite, and bonding laminae together to form a monolithic structure. During Phase I four compositions were synthesized with characteristics which appear suitable for monolithic array operation. One of these compositions, LM71B, has been used in Phase II to successfully obtain memory operation in monolithic arrays. Processes for making thin sheets of uniform thickness have been developed; one was based upon the thermoplastic flow properties of the binder system for sheets thicker than one mil and another was based on a doctor-blade process for sheets thinner than one mil. A process has been developed for making conductors that match the shrinkage of the ferrite when fired, by bisque firing sheets made from a Pt-alloy paste. A process has been developed to expose the conductors at the edge of the array to facilitate making of connections. A process for embossing laminae and for embedding the conductors has been developed. Finally a process for bonding laminae to form a monolithic structure has also been developed.

Twenty-two full-size arrays were fabricated and fired during the development of these processes; 14 were partially populated and 8 were fully populated. The majority of these were tested for their memory characteristics as well as for their physical characteristics. The disturbed output signals under standard operating conditions for these arrays varied from an average of nearly 3.0 millivolts to 1.5 millivolts. The disturbed signal level decreased with improved process control due to less penetration of the conductors into the insulating lamina during the bonding process. The disturbed signal level increased to 4 millivolts (a 165% increase) with an increase in read and write currents of only 30% over the standard conditions.

The arrays produced during this program meet the essential goals and demonstrate the feasibility of fabricating monolithic ferrite memory arrays by the processes developed. It is recommended that the processes used to fabricate the 270 word, 35 bit arrays in this program be further

developed and improved, and that arrays be produced in sufficient quantity for construction and test of a feasibility model monolithic ferrite memory system.

The specific process improvements are: (1) reduction of conductor resistance to lower signal attenuation along the digit-sense line, (2) reduction of thickness of center lamina to increase the disturbed signal output, (3) extension of the conductors to facilitate making of interconnections, (4) refinement of the embossing process to form channels that are more rectangular in shape and uniform in depth, and (5) refinement of the bonding process to obtain a more uniform bond between laminae.

NASA-Langley, 1972 —— 10 CR-2152

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